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# MUNICIPAL WASTE COMBUSTORS - BACKGROUND INFORMATION FOR PROPOSED STANDARDS: POST-COMBUSTION TECHNOLOGY PERFORMANCE

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# Municipal Waste Combustors-Background Information for Proposed Standards: Post-Combustion Technology Performance

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16. ABSTRACT

This document evaluates the performance of various air pollution control devices applied to new and existing municipal waste combustors (MWC's). The control devices analyzed include electrostatic precipitators (ESP's), furnace sorbent injection systems with ESP's, moderate- and low-temperature duct sorbent injection systems with ESP's, or fabric filters (FF's) and spray dryers with ESP's or FF's. The removal capabilities for each of these control devices are evaluated for particulate matter, metals (arsenic, cadmium, chromium, lead, mercury, and nickel), chlorinated dibenzo-p-dioxins and dibenzofurans, and acid gases, sulfur dioxide and hydrogen chloride.

The available data for each of the control devices listed, as applied to MWC's, is presented. The key process parameters affecting control device performance are discussed. Performance is correlated with these parameters to determine the highest achievable removal efficiencies for each pollutant.

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# BACKGROUND INFORMATION FOR
# PROPOSED STANDARDS: POST-COMBUSTION TECHNOLOGY PERFORMANCE

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# 1.0 INTRODUCTION

## 1.1 OVERVIEW OF REPORT

This document evaluates the performance of various air pollution control devices applied to new and existing municipal waste combustors (MWC's). The control devices analyzed include electrostatic precipitators (ESP's), furnace sorbent injection systems with ESP's, duct sorbent injection systems with ESP's and fabric filters (FF's), and spray dryers with ESP's and FF's. Each control device is discussed in a separate section of this document. Performance capabilities of each control device are evaluated for the following pollutants: particulate matter (PM), metals (arsenic, cadmium, chromium, lead, mercury, and nickel), chlorinated dibenzo-p-dioxins and dibenzofurans (CDD/CDF), and acid gases (sulfur dioxide [$SO_2$] and hydrogen chloride [HCl]).

These evaluations include assessments of the key parameters affecting control device performance for the various pollutants and the development of correlations between parameters and performance to establish operating conditions that yield high removal efficiencies and low emission rates for each pollutant.

## 1.2 OVERVIEW OF UNCONTROLLED EMISSIONS

This section presents information on uncontrolled air emissions from MWC's. This information is presented to provide a basis for comparison with controlled emissions at facilities where data on uncontrolled emission levels are not available. Information is presented for PM, metals, CDD/CDF, and acid gases (HCl and $SO_2$) for each major combustor type.

### 1.2.1 Particulate Matter

Particulate emissions data collected at the inlet to the pollution control device are summarized in "Municipal Waste Combustion Assessment: Combustion Control at Existing Facilities" and are presented in Table 1-1. From mass burn refractory wall combustors, typical uncontrolled PM concentrations are 3 grains per dry standard cubic foot (gr/dscf) at 7 percent oxygen ($O_2$). Typical uncontrolled concentrations for mass burn waterwall, mass burn rotary waterwall, and modular excess air combustors are

TABLE 1-1. SUMMARY OF UNCONTROLLED PARTICULATE MATTER CONCENTRATIONS[1]

| Combustor Type | Concentration (gr/dscf at 7% $O_2$) |
|---|---|
| Mass burn refractory wall | 3 |
| Mass burn waterwall;<br>Mass burn rotary waterwall;<br>Modular excess air | 2 |
| Refuse-derived fuel fired | 4 |
| Modular starved air | 0.15 |

2 gr/dscf. At refuse derived fuel (RDF) combustors, typical uncontrolled PM concentrations are 4 gr/dscf and at modular starved air combustors, typical uncontrolled PM concentrations are 0.15 gr/dscf. Particulate data presented in this document are generally normalized to 12 percent carbon dioxide ($CO_2$), which results in values approximately six percent lower than when normalized to 7 percent $O_2$.

### 1.2.2 Metals

Emissions of metals in flue gas from MWC's potentially have adverse health effects. Certain metals considered to have the greatest effect--arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), and nickel (Ni) -- have been measured in flue gas emissions from a number of MWC's. Uncontrolled metal concentrations measured at individual MWC's are summarized in Table 1-2 along with average concentrations for each combustor type. All concentrations are presented in micrograms per dry, standard cubic meter (ug/dscm) normalized to 7 percent $O_2$.

Based on the available data, the highest uncontrolled arsenic levels are from RDF combustors which average 615 ug/dscm and range from 203 to 1,060 ug/dscm. The data on mass-burn combustors average 216 ug/dscm and range from

## TABLE 1-2. SUMMARY OF UNCONTROLLED METALS CONCENTRATIONS

| Site | Concentration (ug/dscm at 7% $O_2$) | | | | | | Reference |
|---|---|---|---|---|---|---|---|
| | As | Cd | Cr | Pb | Hg | Ni | |
| Mass Burn | | | | | | | |
| Baltimore RESCO | 226 | NM[a] | 2,960 | NM | NM | NM | 2 |
| Commerce (1987) | 220 | 2,700 | 730 | 50,000 | 450 | 680 | 3 |
| Commerce (1988)[b] | 74 | 1,600 | 3,450 | 17,200 | 450 | 4,000 | 4 |
| Dayton | 234 | 1,550 | 185 | 38,400 | 1,030 | 94 | 5 |
| Gallatin | 422 | 3,130 | 1,040 | 36,300 | 248 | NM | 6 |
| Marion County | NM | 1,120 | 422 | 20,500 | NM | 12 | 7 |
| Quebec City (pilot) | 128 | 1,220 | 1,870 | 34,700 | 373 | 1,300 | 8 |
| Average | 216 | 1,890 | 1,520 | 32,800 | 510 | 1,220 | |
| Modular | | | | | | | |
| Cattaraugus County | 34 | 1,090 | 1,210 | 20,400 | 1,130 | 1,260 | 9 |
| Prince Edward Island | 14 | 1,120 | 71 | 18,400 | 921 | 553 | 10 |
| Tuscaloosa | 99 | NM | 34 | NM | NM | NM | 11 |
| Average | 49 | 1,110 | 436 | 19,400 | 1,020 | 905 | |
| RDF | | | | | | | |
| Biddeford | 583 | 1,280 | 3,170 | 31,300 | 440 | NM | 12 |
| Mid-Connecticut | 1,060 | 1,070 | 927 | 37,400 | 1,010 | 541 | 13 |
| NSP Red Wing | 203 | 805 | 381 | 24,300 | 140 | 344 | 14 |
| Average | 615 | 1,050 | 1,490 | 31,000 | 530 | 443 | |

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[a] NM = Not measured.

[b] Tests conducted firing a mixture of residential and commercial refuse. Tests firing only commercial refuse yielded similar emissions, but are not reported here.

24 to 422 ug/dscm. Modular combustors average 49 ug/dscm for uncontrolled arsenic, with a range of 14 to 99 ug/dscm.

Uncontrolled cadmium levels are similar for all combustor types. At mass burn combustors, uncontrolled cadmium concentrations average 1,890 ug/dscm. From RDF combustors, uncontrolled cadmium emission average 1,050 ug/dscm. Uncontrolled cadmium emissions from modular combustors average 1,110 ug/dscm.

Chromium emissions from the combustor vary widely from facility to facility. At mass burn combustors, uncontrolled emissions range from 185 to 3,450 ug/dscm and average 1,520 ug/dscm. Similarly, uncontrolled chromium emissions from RDF combustors vary between 381 and 3,170 ug/dscm and average 1,490 ug/dscm. At modular units, uncontrolled chromium levels range between 34 and 1,210 ug/dscm and average 436 ug/dscm.

Uncontrolled lead emissions are the highest of any of the metals presented in Table 1-1 and are relatively consistent within a combustor type. Uncontrolled lead emissions from mass burn combustors average 32,800 ug/dscm. From RDF combustors, the average uncontrolled lead emissions are 31,300 ug/dscm. Uncontrolled lead emissions from modular MWC's average 19,400 ug/dscm.

Uncontrolled mercury emissions vary widely from facility to facility. From mass burn combustors, uncontrolled mercury emissions range from 250 to 1,030 ug/dscm and average 510 ug/dscm. Uncontrolled values for RDF combustors are between 140 and 1,010 ug/dscm, averaging 530 ug/dscm. The available uncontrolled mercury emissions data from modular units are 920 and 1,130 ug/dscm, for an average of 1,020 ug/dscm.

Uncontrolled nickel emissions also vary significantly from each facility. For mass burn combustors, uncontrolled nickel emissions range from 12 to 4,000 ug/dscm and average 1,220 ug/dscm. The uncontrolled nickel emissions data available for RDF combustors are 344 and 540 ug/dscm for an average of 443 ug/dscm. Uncontrolled nickel emissions for two modular combustors are 550 and 1,260 ug/dscm, for an average of 905 ug/dscm.

The average uncontrolled metals concentrations are used in this document to estimate removal efficiencies at individual MWC's where uncontrolled metals emissions are not available. Arsenic, cadmium, chromium, lead, and nickel are associated with particulate and are consistently removed to relatively low levels across a particulate control device. Thus, the estimated removal efficiency is probably a reasonable approximation of the actual removal efficiency. For mercury, however, with the relatively wide variation in uncontrolled mercury concentrations and the general understanding that mercury is not associated with particulate, a realistic mercury removal efficiency cannot be estimated with the available data unless the outlet mercury concentration is substantially lower than the lowest reported uncontrolled mercury concentration. Thus, outlet mercury emissions data in this document are only compared to the range in uncontrolled mercury concentrations in Table 1-2 to indicate whether mercury removal may have occurred.

### 1.2.3 CDD/CDF

Uncontrolled CDD/CDF emission levels are summarized in "Muncipal Waste Combustion Assessment: Combustion Control at Existing Facilities" and are presented in Table 1-3. All concentrations reflect the sum of the tetra- through octa-chlorinated CDD/CDF homologues and are presented in nanograms per dry, standard cubic meter (ng/dscm) normalized to 7 percent $O_2$. From mass burn refractory combustors, typical uncontrolled CDD/CDF concentrations

TABLE 1-3. SUMMARY OF UNCONTROLLED CDD/CDF CONCENTRATIONS[15]

| Combustor Type | Concentration (ng/dscm at 7% $O_2$) |
|---|---|
| Mass burn refractory | 4,000 |
| Mass burn waterwall - large | 500 |
| Mass burn waterwall - midsize;<br>Modular excess air | 200 |
| Mass burn waterwall - small;<br>Refuse-derived fuel fired;<br>Mass burn rotary waterwall | 2,000 |
| Modular starved air | 400 |

are 4,000 ng/dscm. At large mass burn waterwall combustors, typical concentrations are 500 ng/dscm. Midsize mass burn waterwall and modular excess air combustors have typical uncontrolled CDD/CDF concentrations of 200 ng/dscm. Three combustor types: small mass burn waterwall, RDF, and mass burn rotary waterwall combustors have typical uncontrolled CDD/CDF concentrations of 2,000 ng/dscm. At modular starved air combustors, typical concentrations are 400 ng/dscm.

### 1.2.4 Acid Gas

Uncontrolled acid gas ($SO_2$ and HCl) emissions are summarized in Table 1-4. All acid gas concentrations are on a dry basis and are presented in parts per million by volume (ppm) normalized to 7 percent $O_2$. For mass burn combustors, uncontrolled $SO_2$ concentrations range from 59 to 330 ppm and average 180 ppm; HCl concentrations range from 450 to 900 ppm and average 650 ppm. Data from the one RDF combustor indicate uncontrolled $SO_2$ emissions of 100 ppm; HCl emissions are 580 ppm. For modular combustors, uncontrolled $SO_2$ concentrations range from 66 to 150 ppm and average 110 ppm; HCl concentrations range from 190 to 570 ppm and average 420 ppm. Average uncontrolled $SO_2$ and HCl concentrations of 200 and 500 ppm are used in this document to estimate removal efficiencies at MWC's for which uncontrolled acid gas data are not available.

## TABLE 1-4. SUMMARY OF UNCONTROLLED ACID GAS ($SO_2$ AND HCl) CONCENTRATIONS

| Site | (ppm, dry at 7% $O_2$) $SO_2$ | HCl | References |
|---|---|---|---|
| Mass Burn | | | |
| Claremont | NM[a] | 450 | 16 |
| Commerce (1987) | 270 | 900 | 17 |
| Commerce (1988) | 110 | 650 | 18 |
| Long Beach | 140 | NM | 19 |
| Marion County (1986) | 180 | 570 | 20 |
| Marion County (1987) | 330 | 680 | 21 |
| Millbury (Unit 1) | 210 | 770 | 22 |
| Millbury (Unit 2) | 300 | 730 | 23 |
| Munich | 92 | 630 | 24 |
| Portland | 300 | NM | 25 |
| Quebec City | 130 | 450 | 26 |
| Stanislans County (Unit 1) | 67 | NM | 27 |
| Stanislans County (Unit 2) | 59 | NM | 28 |
| Average | 180 | 650 | |
| Modular | | | |
| Cattaraugus | 150 | 190 | 29 |
| Prince Edward Island | 66 | 490 | 30 |
| St. Croix | 120 | 570 | 31 |
| Average | 110 | 420 | |
| RDF | | | |
| Biddeford | 100 | 580 | 32 |

[a] NM = Not measured.

## 1.3 REFERENCES

1. U.S. Environmental Protection Agency. Municipal Waste Combustion Assessment: Combustion Control at Existing Facilities. EPA-600/8-89-058. August 1989.

2. PEI Associates, Inc. Method Development and Testing for Chromium, No. 2 Refuse-to-Energy Incinerator, Baltimore RESCO. (Prepared for U. S. Environmental Protection Agency. Research Triangle Park, North Carolina EMB Report 85-CHM8. EPA Contract No. 68-02-3849. August 1986.

3. McDannel, M. D., L. A. Green, and B. L. McDonald (Energy Systems Associates). Air Emissions Tests at Commerce Refuse-to-Energy Facility, May 26 - June 5, 1987. Prepared for County Sanitation Districts of Los Angeles County. Whittier, California, July 1987.

4. McDannel, M. D., L. A. Green, and A. C. Bell (Energy Systems Associates). Results of Air Emission Test During the Waste-to-Energy Facility. Prepared for County Sanitation Districts of Los Angeles County, Whittier, California. December 1988.

5. Radian Corporation. Preliminary Data from October - November 1988 Testing at the Montgomery County South Plant, Dayton, Ohio.

6. Cooper Engineers, Inc. Air Emissions Tests of Solid Waste Combustion in a Rotary Combustion/Boiler System at Gallatin, Tennessee. Prepared for West County Agency of Contra Costa County, California. July 1984.

7. Vancil, M. A. and C. L. Anderson (Radian Corporation). Summary Report, CDD/CDF, Metals, HCl, $SO_2$, $NO_x$, CO and Particulate Testing, Marion County Solid Waste-to-Energy Facility, Inc., Ogden Martin Systems of Marion, Brooks, Oregon. Prepared for U. S. Environmental Protection Agency, Research Triangle Park, North Carolina. EMB Report No. 86-MIN-03A. September 1988.

8. The National Incinerator Testing and Evaluation Program: Air Pollution Control Technology. EPS 3/UP/2, Environment Canada, Ottowa, September 1986.

9. New York State Department of Environmental Conservation. Emission Source Test Report -- Preliminary Test Report on Cattaraugus County ERF. August 5, 1986.

10. Environment Canada. The National Incinerator Testing and Evaluation Program: Two Stage Combustion. Report EPS 3/up/1. September 1985.

11. PEI Associates, Inc. Method Development and Testing for Chromium, Municipal Refuse Incinerator, Tuscaloosa Energy Recovery, Tuscaloosa, Alabama. Prepared for U.S. Environmental Protection Agency. Research Triangle Park, North Carolina. EMB Report 85-CHM-9. EPA Contract No. 68-02-3849. January 1986.

12. Klamm, S., G. Scheil, M. Whitacre, J. Surman (Midwest Research Institute), and W. Kelly (Radian Corporation). Emission Testing at an RDF Municipal Waste Combustor. Prepared for U. S. Environmental Protection Agency, North Carolina. EPA Contract No. 68-02-4453, May 6, 1988.

13. Anderson, C. L. (Radian Corporation). CDD/CDF, Metals, and Particulate Emissions Summary Report, Mid-Connecticut Resource Recovery Facility, Hartford, Connecticut. Prepared for U. S. Environmental Protection Agency, Research Triangle Park, North Carolina. EMB Report No. 88-MIN-09A. January 1989.

14. Interpoll Laboratories. Results of the March 21 - 26, 1988, Air Emission Compliance Test on the No. 2 Boiler at the Red Wind Station, Test IV (High Load). Prepared for Northern States Power Company, Minneapolis, Minnesota. Report No. 8-2526. May 10, 1988.

15. U.S. Environmental Protection Agency. Municipal Waste Combustion Assessment: Combustion Control at Existing Facilities. EPA-600/8-89-058. August 1989.

16. Almega Corporation. SES Claremont, Claremont, NH, NH/VT Solid Waste Facility. Unit 1 and Unit 2, EPA Stack Emission Compliance Tests, May 26, 27, and 29, 1987. Prepared for Clark-Kenith, Inc. Atlanta, Georgia. July 1987.

17. McDannel, M. D., L. A. Green, and A. C. Bell (Energy Systems Associates). Results of Air Emission Test During the Waste-to-Energy Facility. Prepared for County Sanitation Districts of Los Angeles County, Whittier, California. December 1988.

18. Radian Corporation. Preliminary Data from October - November 1988 Testing at the Montgomery County South Plant, Dayton, Ohio.

19. Ethier, D. D., L. N. Hottenstein, and E. A. Pearson (TRC Environmental Consultants). Air Emission Test Results at the Southeast Resource Recover6y Facility Unit 1, October - December, 1988. Prepared for Dravo Corporation, Long Beach, California. February 28, 1989.

20. Vancil, M. A. and C. L. Anderson (Radian Corporation). Summary Report, CDD/CDF, Metals, HCl, $SO_2$, $NO_x$, CO and Particulate Testing, Marion County Solid Waste-to-Energy Facility, Inc., Ogden Martin Systems of Marion, Brooks, Oregon. Prepared for U. S. Environmental Protection Agency, Research Triangle Park, North Carolina. EMB Report No. 86-MIN-03A. September 1988.

21. Anderson, C. L., et. al. (Radian Corporation). Characterization Test Report, Marion County Solid Waste-to-Energy Facility, Inc., Ogden Martin Systems of Marion, Brooks, Oregon. Prepared for U. S. Environmental Protection Agency, Research Triangle Park, North Carolina. EMB Report No. 86-MIN-04. September 1988.

22. Entropy Environmentalists, Inc. Emissions Testing Report, Wheelabrator Millbury, Inc. Resource Recovery Facility, Millbury, Massachusetts, Unit Nos. 1 and 2, February 8 through 12, 1988. Prepared for Rust International Corporation. Reference No. 5605-B. August 5, 1988.

23. Entropy Environmentalists, Inc. Emissions Testing Report, Wheelabrator Millbury, Inc. Resource Recovery Facility, Millbury, Massachusetts, Unit Nos. 1 and 2, February 8 through 12, 1988. Prepared for Rust International Corporation. Reference No. 5605-B. August 5, 1988.

24. Hahn, J. L., et. al., (Cooper Engineers) and J. A. Finney, Jr. and B. Bahor (Belco Pollution Control Corp.). Air Emissions Tests of a Deutsche Babcock Anlagen Dry Scrubber System at the Munich North Refuse-Fired Power Plant. Presented at: 78th Annual Meeting of the Air Pollution Control Association. Detroit, Michigan. June 1985.

25. Engineering Science, Inc. A Report on Air Emission Compliance Testing at the Regional Waste Systems, Inc. Greater Portland Resource Recovery Project. Prepared for Dravo Energy Resources, Inc. Pittsburg, Pennsylvania. March 1989.

26. The National Incinerator Testing and Evaluation Program: Air Pollution Control Technology. EPS 3/UP/2, Environment Canada, Ottowa, September 1986.

27. Hahn, J. L. (Ogden Projects, Inc.) Environmental Test Report. Prepared for Stanislaus Waste Energy Company Crows Landing, California. OPI Report No. 177R. April 7, 1989.

28. Hahn, J. L. (Ogden Projects, Inc.) Environmental Test Report. Prepared for Stanislaus Waste Energy Company Crows Landing, California. OPI Report No. 177R. April 7, 1989.

29. New York State Department of Environmental Conservation. Emission Source Test Report -- Preliminary Test Report on Cattaraugus County ERF. August 5, 1986.

30. Environment Canada. The National Incinerator Testing and Evaluation Program: Two Stage Combustion. Report EPS 3/up/1. September 1985.

31. Interpoll Laboratories, Inc. Results of the June 6, 1988, Scrubber Performance Test at the St. Croix Waste to Energy Incineration Facility in New Richmond, Wisconsin. Prepared for Interel Corporation. Englewood, Colorado. Report No. 8-2560I. September 20, 1988.

32. Klamm, S., G. Scheil, M. Whitacre, J. Surman (Midwest Research Institute), and W. Kelly (Radian Corporation). Emission Testing at an RDF Municipal Waste Combustor. Prepared for U. S. Environmental Protection Agency, North Carolina. EPA Contract No. 68-02-4453, May 6, 1988.

# 2.0 ELECTROSTATIC PRECIPITATORS

Section 2.0 describes the performance of electrostatic precipitators. Electrostatic precipitators have been used extensively to reduce particulate matter emissions from MWC's. Section 2.1 describes ESP design and operating characteristics. Section 2.2 describes the available emissions test data from ESP-equipped MWC's. In Section 2.3, ESP performance is evaluated for PM, metals, and CDD/CDF. Because ESP's are not designed to reduce emissions of acid gases, data on $SO_2$, HCl, and nitrogen oxides ($NO_x$) are not presented in this section.

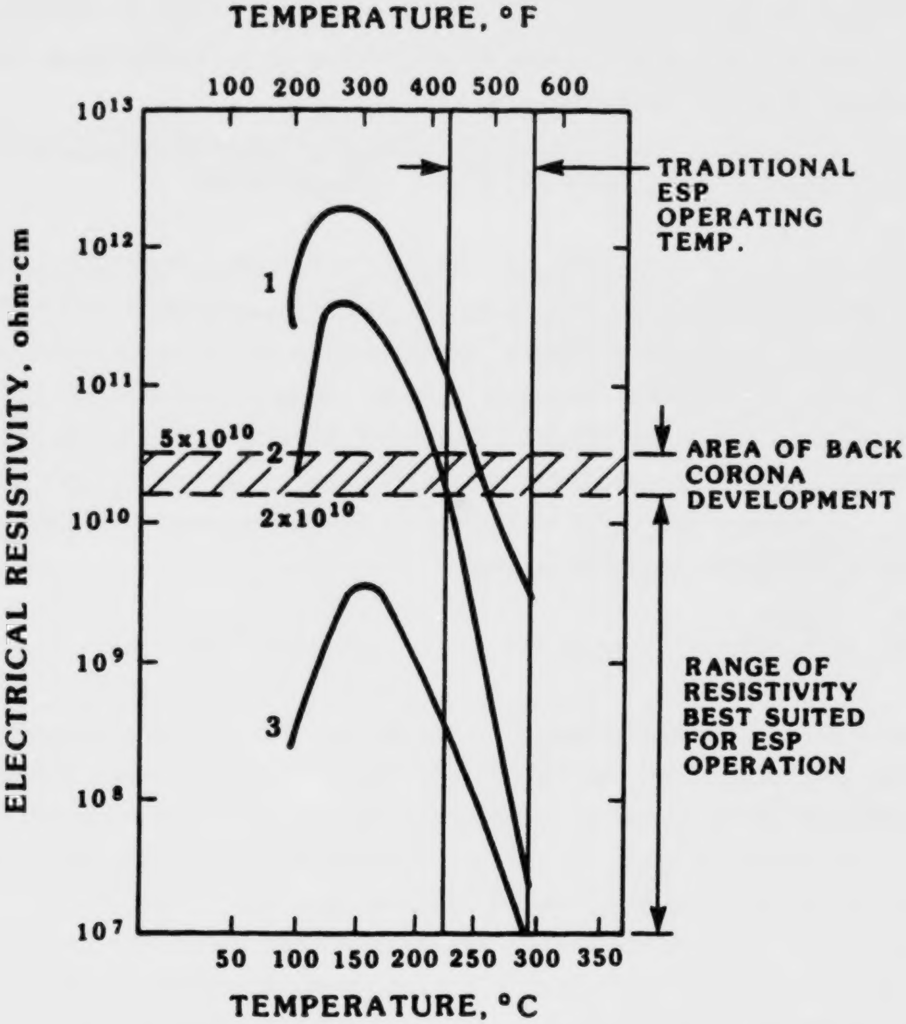
## 2.1 PROCESS DESCRIPTION

Electrostatic precipitators consist of a series of high voltage (20 to 100 kV) discharge electrodes and grounded metal plates through which PM-laden flue gas flows. Negatively charged ions formed by this high voltage field (known as a "corona") attach to PM in the flue gas, causing the charged particles to migrate toward and be collected on the grounded plates. As a general rule, the greater the amount of collection plate area, the greater the ESP's PM collection efficiency. The most common ESP types used by MWC's are: (1) plate-wire units in which the discharge electrode is a bottom-weighted or rigid wire and (2) flat plate units which use flat plates rather than wires as the discharge electrode. Plate-wire ESP's are generally better suited for use with fly ashes with large amounts of small particulate and with large flue gas flow rates (>200,000 actual cubic feet per minute [acfm]). Flat plate units are less sensitive to back corona problems and are thus well suited for use with high resistivity PM.[1] Both of these ESP types have been widely used on MWC's in the U. S., Europe, and Japan.

The layer of particles collected on the plates is removed by rapping, washing, or other methods. When this dust layer is removed, some of the collected PM is reentrained in the flue gas. To assure good PM collection efficiency during plate cleaning and electrical upsets, ESP's have multiple fields located in series along the direction of flue gas flow that can be energized and cleaned independently. Particles reentrained when the collected PM is removed from one field can be recollected in a downstream field.[2] Because of this phenomena, increasing the number of fields generally improves particulate removal efficiency.

In general, fly ashes with resistivities between 1 x $10^8$ and 5 x $10^{10}$ ohm-cm and with a minimum of very fine particles (<1 micron) are most efficiently collected. If the resistivity of the collected PM exceeds roughly 2 x $10^{10}$ ohm-cm, the collected PM layer may have sufficient electrical charge to create a "back corona" phenomenon that interferes with the migration of charged fly ash particles to the collecting electrode and significantly reduces collection efficiency. At resistivities below $10^8$ ohm-cm, the electrical charge on individual particles may be so low that reentrainment of collected dust during electrode cleaning or simply as a result of contact with moving flue gas can become severe.[3] Resistivity is greatly affected by temperature, as shown in a graph of resistivity versus temperature for three municipal solid waste (MSW) fly ashes in Figure 2-1. Most ESP's on MWC's have traditionally operated at 440 to 550$^0$F (225 to 290$^0$C) to avoid potential problems with ash resistivity.[4] However, individual ESP's with temperatures as low as 380$^0$F (195$^0$C) and as high as 600$^0$F (315$^0$C) are currently operating in the U. S. A concern with ESP operation at lower temperatures is the potential for acid corrosion of cool material surfaces due to HCl condensation.

Small particles generally migrate toward the collection plates more slowly than large particles, and are therefore more difficult to collect. This factor is especially important to MWC's because of the amount of total fly ash less than 1 micron. For MWC's, 20 to 70 percent of the fly ash at the ESP inlet is less than 1 micron.[5] In comparison, for pulverized coal-fired combustors, only 1 to 3 percent of the fly ash is generally less than 1 micron. Effective collection of MWC PM will require greater collection areas and lower flue gas velocities than many other types of PM.



[1] Samples taken at furnace outlet on a 250 ton/day municipal incinerator using a dry separation chamber for particulate control.

[2] Samples taken at furnace outlet and exhaust stack inlet on a 250 ton/day municipal incinerator using a wet baffle cooling chamber for particulate control.

[3] Samples taken at furnace outlet and exhaust stack outlet on a 120 ton/day municipal incinerator using a vertical wetted baffle particulate collection device.

Source: Walker, A.B. and Schmitz, Characteristics of Furnace Emissions from Large Mechanically-Stoked Municipal Incinerators, Research-Cottrell

Figure 2-1. Electrical Resistivity of Municipal Incinerator Dust[3]

The collection efficiency of an ESP can be estimated using the Deutsch- Anderson equation:

$$\text{Collection Efficiency (\%)} = (1 - \exp(-Aw/V))100$$

where exp is the natural log (2.718...), A is the surface area of the collecting electrodes ($ft^2$), w is the effective migration velocity of individual PM particles toward the collecting electrode (ft/sec), and V is the actual flue gas flow rate (acfm). However, because of variations in the size and resistivity of individual particles in the flue gas, the effective migration velocity of bulk fly ash is not easily defined.

To account for these variations in PM characteristics, the modified Deutsch-Anderson equation is used:

$$\text{Collection Efficiency (\%)} = (1 - \exp(-Aw/V)^k)100$$

where k is a constant (generally around 0.5, but can vary between 0.4 and 0.8) that depends on the electrical resistivity and size of the fly ash particles and w is now an empirically derived migration velocity.

As an approximate indicator of collection efficiency, the specific collection area (SCA) of an ESP is frequently used. The SCA is calculated by dividing the collecting electrode plate area by the actual flue gas flow rate (A/V in the Deutsch-Anderson equation) and is expressed as square feet of collecting area per 1,000 acfm of flue gas. In general, the higher the SCA, the higher the collection efficiency.

One problem encountered with existing ESP's is the amount of particulate bypass around the ESP ionizing fields and collection plates. This bypass limits the level to which outlet PM emissions can be reduced. New ESP's can be designed to significantly reduce the amount of bypass.

A recently identified concern with the operation of MWC ESP's is the potential for formation of CDD/CDF across the ESP. The mechanism and extent of formation is poorly understood, but is believed to be promoted by copper in MWC fly ash, carbon in the PM, and surface area for reaction at temperatures between roughly 450 and $650^0$F.[6]

## 2.2 SUMMARY OF TEST DATA

Section 2.2 provides emissions data from various ESP-equipped MWC facilities. The facilities are limited to those which were constructed after 1984 and were designed for good particulate control. Data for ESP's built before 1984 show a substantially lower level of performance. Section 2.2.1 covers mass burn combustors, Section 2.2.2 covers modular (excess-air and starved-air) combustors, and Section 2.2.3 covers RDF combustors. A summary of the emissions data is provided for each facility.

### 2.2.1 Mass Burn MWC's

2.2.1.1 Alexandria.[7] The Alexandria/Arlington Resource Recovery Facility in Alexandria, Virginia, consists of three identical 325 ton/day (tpd) Martin GmbH waterwall combustors. Emissions from each combustor are controlled with a 3-field ESP. The flue gas temperature at the ESP outlet is generally about $340^{0}$F with a gas flow of about 67,000 acfm (40,000 dry standard cubic feet per minute [dscfm]). The ESP's are designed to meet a PM emission limit of 0.03 gr/dscf at 12 percent $CO_2$. Dry hydrated lime can be injected into the combustor with the overfire air for acid gas control.

In December 1987, tests were performed to demonstrate compliance with operating permits. The tests were conducted under normal operating conditions with dry hydrated lime injection on Unit 1 and without lime injection on Units 2 and 3. The test results without lime injection are reported here. The test results with lime addition are reported in Section 3.2.1. Flue gas was sampled at the ESP outlet for PM on the three test runs conducted without dry lime injection.

The PM data from the tests without lime injection are summarized in Table 2-1. Flue gas flow rate and temperature were relatively constant among each of the runs. Measured PM emissions from Unit 2 ranged from 0.029 to 0.031 gr/dscf at 12 percent $CO_2$ and averaged 0.030 gr/dscf.

## TABLE 2-1. PARTICULATE DATA FOR ALEXANDRIA WITHOUT LIME INJECTION

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F)[b] | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 2-1 | 360 | 64,500 | 0.029 |
| ESP = Normal | 2-2 | 366 | 66,200 | 0.031 |
| | 2-3 | 366 | 64,900 | 0.029 |
| Average (Unit 2) | | 364 | 65,200 | 0.030 |
| | 3-1 | 367 | 62,800 | 0.013 |
| | 3-2 | 363 | 66,200 | 0.012 |
| | 3-3 | 362 | 66,500 | 0.051 |
| Average (Unit 3) | | 364 | 65,200 | 0.025 |

[a] Run Number contains the unit number followed by the run number on that unit.

[b] Estimated from measured temperature at ESP outlet and an assumed temperature drop across the ESP (20°F).

Particulate emissions from Unit 3 ranged from 0.012 to 0.051 gr/dscf and averaged 0.025 gr/dscf. Thus, both units are capable of meeting the permit PM emission limit of 0.03 gr/dscf.

2.2.1.2 Baltimore RESCO.[8,9] The Baltimore RESCO facility in Baltimore, Maryland, consists of three identical 750 ton/day, Von Roll, waterwall combustors. Particulate emissions from each combustor are controlled by a 4-field, wire/plate ESP designed by Wheelabrator Frye. Each ESP has a design SCA of 577 $ft^2$/1,000 acfm. The flue gas flow at the ESP inlet is typically about 240,000 acfm (123,000 dscfm) at a temperature of $460^0$F, although the ESP has operated at lower temperatures ($380^0$F). The ESP exhaust streams are separately ducted and routed through an induced-draft (ID) fan into a common stack.

In January 1985, tests were conducted to demonstrate compliance with permit conditions for all three combustor trains. At the ESP outlet, three runs were conducted on each unit in which PM, $SO_2$, fluorides, solid and gaseous chlorides, and $NO_x$ were measured. In May 1985, testing was done on Unit 2 at the ESP inlet and outlet as part of a method development effort for chromium. These tests were conducted to measure chromium, arsenic, and PM. Although these tests were designed to provide emissions data under normal operating conditions, the steam load was only 85 percent of normal during these tests.

Particulate data from both test programs are presented in Table 2-2. For all runs conducted, outlet PM emissions did not exceed 0.007 gr/dscf at 12 percent $CO_2$. The average outlet PM concentrations were 0.0020, 0.0044, and 0.0010 gr/dscf at Units 1,2, and 3, respectively, for the compliance tests. At Unit 2 at 85 percent steam load, the outlet PM emissions averaged 0.0027 gr/dscf, with an average PM removal efficiency of greater than 99.9 percent. Although the flue gas flow rate was approximately 60 percent higher during the 85 percent steam load tests on Unit 2, yielding lower SCA values (570 versus 910 $ft^2$/1,000 acfm), outlet PM emissions were similar. This suggests that increasing the SCA above the design value by decreasing the flue gas flow does not necessarily improve PM performance of the ESP.

TABLE 2-2. PARTICULATE DATA FOR BALTIMORE RESCO

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal | 1-1 | 385[b] | 176,100 | NM[c] | 0.0004 | - |
| ESP = Normal | 1-2 | 385[b] | 171,600 | NM | 0.0017 | - |
| | 1-3 | 377[b] | 161,400 | NM | 0.0038 | - |
| Average (Unit 1) | | 382 | 169,700 | NM | 0.0020 | - |
| | 2-1 | 365[b] | 153,700 | NM | 0.0066 | - |
| | 2-2 | 366[b] | 150,800 | NM | 0.0032 | - |
| | 2-3 | 369[b] | 149,100 | NM | 0.0035 | - |
| Average (Unit 2) | | 367 | 151,200 | NM | 0.0044 | - |
| | 3-1 | 375[b] | 147,400 | NM | 0.0014 | - |
| | 3-2 | 371[b] | 134,400 | NM | 0.0004 | - |
| | 3-3 | 370[b] | 136,700 | NM | 0.0013 | - |
| Average (Unit 3) | | 372 | 139,500 | NM | 0.0010 | - |
| Combustor = 85% load | 2-1 | 465 | 239,000 | 2.27 | 0.0030 | 99.9 |
| ESP = Normal | 2-2 | 463 | 251,400 | 2.03 | 0.0030 | 99.9 |
| | 2-3 | 462 | 236,800 | 1.86 | 0.0020 | 99.9 |
| Average (85% Load) | | 453 | 242,400 | 2.05 | 0.0027 | 99.9 |

[a] Run Number contains unit number followed by run number on that unit.

[b] Estimated from temperature measured at ESP outlet and an assumed temperature drop across the ESP (11°F) based on measured values for other tests.

[c] NM = Not measured.

Chromium and arsenic data from Baltimore are presented in Table 2-3. Removal efficiencies for both metals were high, 97 percent for arsenic and 99 percent for chromium.

2.2.1.3 Bay County.[10] The Bay County Resource Management Facility in Panama City, Florida, is designed to combust MSW or MSW with wood chips in two identical 255 tons/day Westinghouse-O'Connor rotary waterwall combustors. Emissions from each combustor are controlled by a 3-field wire/plate ESP manufactured by Environmental Elements Corporation. At the ESP inlet, the design flue gas temperature is $400^0$F and the flow is 56,000 acfm. Each ESP has an SCA of 350 $ft^2$/1,000 acfm and is designed to achieve 99 percent PM removal. The permitted outlet PM concentration is 0.03 gr/dscf at 12 percent $CO_2$. The flue gas exits through individual flues in a single 125-ft high stack.

Compliance tests were conducted in June 1987. Particulate emissions were measured at the ESP outlet for three tests at each unit. The results from the tests are presented in Table 2-4. Only MSW was combusted during the tests. The PM emissions from Unit 1 ranged from 0.014 to 0.024 gr/dscf at 12 percent $CO_2$ and averaged 0.019 gr/dscf. At Unit 2, PM emissions ranged from 0.019 to 0.029 gr/dscf and averaged 0.024 gr/dscf. Inlet PM was not measured. Both units were able to demonstrate emissions less than the permit level of 0.03 gr/dscf.

2.2.1.4 Dayton.[11] The Montgomery County South Incinerator plant in Dayton, Ohio, includes three nearly identical Volund refractory-lined combustors. Two 300-tpd units were built in 1970 and a third 300-tpd unit was built in 1988. Limestone can be injected through a single injection port into the furnace ignition chamber of each unit to reduce $SO_2$ emissions. Typically, the unit operates with 250 lb/hr limestone injection. Water sprays are used to cool the flue gas exiting the combustor. Emissions are controlled by United-McGill 3-field plate-to-plate ESP's made of Cor-ten steel. Each ESP has a design SCA of 326 $ft^2$/1,000 acfm. The design flue gas flow rate at the ESP inlet is 100,000 acfm at a temperature of 450 to $600^0$F,

TABLE 2-3. METALS EMISSIONS DATA FOR BALTIMORE RESCO

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Inlet Concentration (ug/dscm at 7% $O_2$) |  | Outlet Concentration (ug/dscm at 7% $O_2$) |  | Removal Efficiency (%) |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | As | Cr | As | Cr | As | Cr |
| Combustor = 85% load | 2-1 | 465 | 0.0030 | NM[b] | 3,600 | NM | 36.5 | -- | 99.0 |
| ESP = Normal | 2-2 | 463 | 0.0030 | NM | 2,560 | NM | 16.2 | -- | 99.4 |
|  | 2-3 | 462 | 0.0020 | 226 | 2,710 | 5.8 | 34.8 | 97.4 | 98.7 |
| Average |  | 463 | 0.0027 | 226 | 2,960 | 5.8 | 29.2 | 97.4 | 99.0 |

[a] Run Number contains unit number followed by run number on that unit.

[b] NM = Not measured.

TABLE 2-4. PARTICULATE DATA FOR BAY COUNTY

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F)[b] | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1-1 | 450 | 52,400 | 0.014 |
| ESP = Normal | 1-2 | 454 | 55,100 | 0.024 |
| | 1-3 | 452 | 52,800 | 0.020 |
| Average (Unit 1) | | 452 | 53,400 | 0.019 |
| | 2-1 | 454 | 52,600 | 0.025 |
| | 2-2 | 474 | 58,100 | 0.019 |
| | 2-3 | 476 | 59,000 | 0.029 |
| Average (Unit 2) | | 468 | 56,600 | 0.024 |

[a] Run Number contains the unit number followed by the run number on that unit.

[b] Estimated from measured temperature at ESP outlet and an assumed temperature drop across the ESP (25°F).

with a typical value of 575°F. Flue gas is exhausted through a common stack for Units 1 and 2. Unit 3 exhausts through a dedicated stack.

In November and December 1988, testing was conducted by EPA on Unit 3. Tests were conducted with furnace sorbent injection, duct sorbent injection, and without sorbent injection. The purpose of these tests was to evaluate ESP performance for the removal of PM, metals, and CDD/CDF at reduced flue gas temperatures at the ESP inlet and to evaluate the effect of sorbent injection. The results from the tests without sorbent injection are reported here. Results of the tests with furnace sorbent injection are reported in Section 3.2.2. Results from the duct sorbent injection tests are reported in Section 4.2.

Testing was performed in two phases: screening and parametric. The screening tests were performed to help select operating conditions for the parametric tests. During the screening tests, measurements of $SO_2$ and HCl were taken at the ESP inlet during all tests and at the ESP outlet for some of the sorbent injection tests. During the parametric testing, flue gas was sampled simultaneously at the ESP inlet and outlet and analyzed for PM, $SO_2$, CDD/CDF, metals (16 metals including arsenic, cadmium, chromium, lead, mercury, nickel, and others), and volatile organics. Hydrogen chloride was measured at the ESP outlet only except for the tests with duct injection during which HCl was measured at both the ESP inlet and outlet. CDD/CDF was also measured at the mixing chamber during several of the tests. Nine test runs were conducted during parametric testing without sorbent injection.

The particulate data from testing without sorbent injection are presented in Table 2-5. The outlet particulate emissions ranged from 0.003 to 0.023 gr/dscf at 12 percent $CO_2$ and averaged 0.011 gr/dscf for seven of the nine test runs. The ESP malfunctioned during Runs 6 and 7, yielding excessive outlet PM levels. During Runs 1 through 5, PM emissions averaged 0.0065 gr/dscf. Particulate removal efficiency during the seven acceptable runs averaged 98.5 percent. No trends were observed in PM removal versus SCA or inlet PM concentration. Outlet PM concentrations tended to be higher with

TABLE 2-5. PARTICULATE DATA FOR DAYTON WITHOUT SORBENT INJECTION

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal<br>ESP = Normal (575°F) | 1 | 567 | 71,800 | 0.376 | 0.0030 | 99.2 |
| | 2 | 548 | 78,000 | 0.568 | 0.011 | 98.1 |
| | 3 | 564 | 80,300 | 0.983 | 0.0057 | 99.4 |
| Average | | 560 | 76,700 | 0.642 | 0.0066 | 98.9 |
| Combustor = Normal<br>ESP = Low (400°F) | 4 | 402 | 79,200 | 0.590 | 0.0038 | 99.4 |
| | 5 | 400 | 72,500 | 0.527 | 0.0087 | 98.4 |
| | 6 | 400 | 66,200 | 0.578 | 0.105[a] | 81.8[a] |
| Average | | 401 | 72,600 | 0.565 | 0.0063[b] | 98.9[b] |
| Combustor = Low mixing chamber temp. (1500°F)<br>ESP = Normal (525°F) | 7 | 559 | 73,400 | 0.378 | 0.123[a] | 67.5[a] |
| | 8 | 559 | 68,900 | 0.725 | 0.022 | 97.0 |
| | 9 | 545 | 82,000 | 0.978 | 0.023 | 97.7 |
| Average | | 554 | 74,800 | 0.684 | 0.023[b] | 97.4[b] |

[a] Erroneous data points because of unstable ESP voltage. Values not included in average.

[b] Average excludes erroneous data points for runs 6 and 7.

higher inlet PM concentrations, but outlet concentrations below 0.01 gr/dscf were achieved even at inlet PM concentrations approaching 1.0 gr/dscf, as shown in Figure 2-2. Thus, the 3-field ESP at Dayton with an SCA of about 320 $ft^2$/1,000 acfm operating at 575$^O$F or less, achieved outlet PM levels of 0.01 gr/dscf at 12 percent $CO_2$ or less.

The metals data from Dayton are presented in Table 2-6. During Runs 1 to 5, removal efficiencies for arsenic, cadmium, and lead were about 98 to 99 percent and were similar to the PM removal efficiencies. Chromium removal efficiencies were somewhat lower, around 95 percent. The metals removal efficiencies were somewhat lower for Runs 8 and 9, as were the PM removal efficiencies. Mercury concentrations at the inlet were not significantly different from the outlet values, indicating that no mercury removal occurred across the ESP.

In Table 2-7, CDD/CDF data are presented. At an ESP inlet set point temperature of 575$^O$F, outlet CDD/CDF concentrations ranged from 7,790 to 22,500 ng/dscm at 7 percent $O_2$ and averaged 17,100 ng/dscm. The inlet CDD/CDF concentrations were between 112 and 391 ng/dscm and averaged 252 ng/dscm. At an ESP inlet set point temperature of 525$^O$F and a lower mixing chamber temperature, outlet CDD/CDF emissions of 13,800 to 15,700 ng/dscm at 7 percent $O_2$ were measured, with an average of 14,500 ng/dscm. The corresponding ESP inlet concentrations were between 150 and 247 ng/dscm and averaged 214 ng/dscm. At the mixing chamber, CDD/CDF concentrations of 552 and 2,450 ng/dscm were measured. At an ESP inlet set point temperature of 400$^O$F, outlet CDD/CDF concentrations ranged from 317 to 1,580 ng/dscm at 7 percent $O_2$ and averaged 866 ng/dscm. The corresponding ESP inlet CDD/CDF concentration ranged from 10.2 to 51 ng/dscm and averaged 32.8 ng/dscm. The mixing chamber CDD/CDF concentrations ranged from 798 to 3,120 ng/dscm and averaged 1,870 ug/dscm for the three runs conducted.

The flue gas temperature at the ESP inlet appears to significantly affect CDD/CDF emissions at the ESP outlet, as shown in Figure 2-3. At 400$^O$F, CDD/CDF emissions are roughly an order of magnitude lower than at 525 to 575$^O$F. Except for Run 1, outlet CDD/CDF emissions at 525$^O$F are 25 to 40 percent lower than emissions at 575$^O$F.

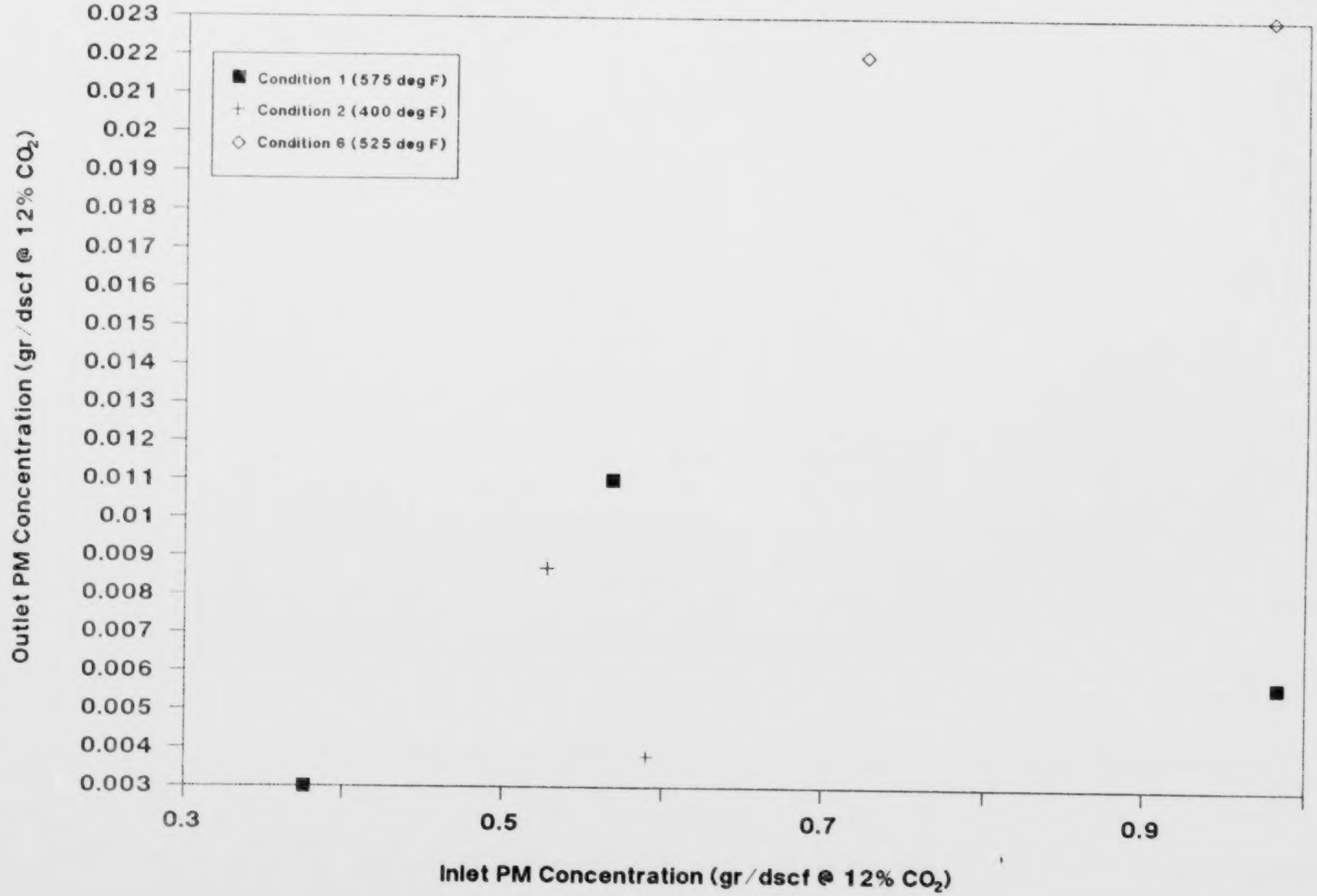


Figure 2-2. Outlet PM concentration as a function of inlet PM concentration at the Dayton MWC.

TABLE 2-6. METALS DATA FOR DAYTON WITHOUT SORBENT INJECTION

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Inlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Removal Efficiency (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal | 1 | 567 | 0.0030 | 189 | 489 | 114 | 27,700 | 845 | 98.6 | 2.17 | 10.5 | 5.91 | 322 | 625 | 3.80 | 98.9 | 97.9 | 94.8 | 98.8 | 26.0 | 96.2 |
| ESP = Normal (575°F) | 2 | 548 | 0.011 | 308 | 2,460 | 170 | 67,300 | 890 | 68.4 | 3.52 | 53.9 | 4.91 | 973 | 1,034 | 2.86 | 98.9 | 97.8 | 97.1 | 98.6 | -16.2 | 95.8 |
| | 3 | 564 | 0.0057 | 168 | 2,905 | 84 | 13,160 | 1,150 | 94.7 | 1.85 | 24.4 | 3.52 | 309 | 1,390 | 1.58 | 98.9 | 99.2 | 95.8 | 97.7 | -20.9 | 98.3 |
| Average | | 560 | 0.0066 | 222 | 1,950 | 123 | 36,050 | 962 | 87.2 | 2.51 | 29.6 | 4.78 | 535 | 1,016 | 2.74 | 98.9 | 98.3 | 95.9 | 98.4 | -3.7 | 96.8 |
| Combustor = Normal | 4 | 402 | 0.0038 | 165 | 1,455 | 150 | 15,635 | 920 | 78.4 | 1.53 | 16.2 | 4.44 | 602 | 631 | 2.12 | 99.1 | 98.9 | 97.0 | 96.2 | 31.4 | 97.3 |
| ESP = Low temp (400°F) | 5 | 400 | 0.0087 | 223 | 930 | 154 | 27,057 | 750 | 59.3 | 4.34 | 22.4 | 9.77 | 515 | 769 | 9.14 | 98.1 | 97.6 | 93.7 | 98.1 | - 2.5 | 84.5 |
| | 6 | 400 | 0.105[a] | 247 | 1,527 | 267 | 56,475 | 1,495 | 104 | 42.9[a] | 283[a] | 46.3[a] | 22,640[a] | 2,053 | 21.5 | 82.6[a] | 81.5[a] | 82.7[a] | 59.9[a] | -37.3 | 79.3[a] |
| Average | | 401 | 0.0063 | 212 | 1,304 | 190 | 33,056 | 1,055 | 80.6 | 2.94 | 19.3 | 7.11 | 559 | 1,150 | 5.63 | 98.6 | 98.3 | 95.4 | 96.7 | - 2.8 | 90.9 |
| Combustor = Low mixing | 7 | 559 | 0.123[a] | 124 | 669 | 156 | 44,048 | 2,255 | 74.9 | 55.6[a] | 702[a] | 58.7[a] | 18,577[a] | 1,816 | 29.6[a] | 55.2[a] | -4.9[a] | 62.4[a] | 57.8[a] | 19.5 | 60.5[a] |
| chamber temp (1500°F) | 8 | 559 | 0.022 | 230 | 1,994 | 242 | 50,598 | 975 | 148 | 10.3 | 69.0 | 11.1 | 1,836 | 1,074 | 9.25 | 95.5 | 96.5 | 95.4 | 96.4 | -10.2 | 93.8 |
| ESP = Normal (525°F) | 9 | 545 | 0.023 | 518 | 1,626 | 309 | 53,781 | 949 | 123 | 11.4 | 89.5 | 10.2 | 3,202 | 1,128 | 4.52 | 97.8 | 94.5 | 96.7 | 94.1 | -18.9 | 96.3 |
| Average | | 554 | 0.023 | 291 | 1,430 | 236 | 49,476 | 1,393 | 115 | 10.9 | 79.3 | 10.7 | 2,519 | 1,229 | 6.89 | 96.7 | 95.5 | 96.1 | 95.3 | -3.2 | 95.0 |
| Overall Average | | 505 | 0.011 | 242 | 1,561 | 183 | 39,527 | 1,137 | 94.4 | 5.03 | 40.9 | 7.14 | 1,109 | 1,148 | 4.75 | 98.2 | 97.5 | 95.8 | 97.0 | -3.2 | 94.6 |

[a] Not included in average because the first field of the ESP was unstable during the test, leading to unusually poor performance.

TABLE 2-7. CDD/CDF DATA FOR DAYTON WITHOUT SORBENT INJECTION

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Mixing Chamber CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal | 1 | 573 | NM[a] | 254 | 7,790 | -2,970 |
| ESP = Normal (575°F) | 2 | 568 | NM | 391 | 22,500 | -5,650 |
| | 3 | 573 | NM | 112 | 21,100 | -18,800 |
| Average | | 571 | NM | 252 | 17,100 | -9,140 |
| Combustor = Normal | 4 | 396 | 552 | 10.2 | 317 | -3,010 |
| ESP = Low temp. (400°F) | 5 | 407 | 2,450 | 37.1 | 704 | -1,790 |
| | 6 | 386 | NM | 51.0 | 1,580 | -3,000 |
| Average | | 396 | 1,500 | 32.8 | 866 | -2,600 |
| Combustor = Low mixing | 7 | 548 | 798 | 150 | 14,000 | -9,230 |
| chamber temp. (1500°F) | 8 | 525 | 3,120 | 247 | 15,700 | -6,260 |
| ESP = Normal (525°F) | 9 | 528 | 1,680 | 247 | 13,800 | -5,490 |
| Average | | 534 | 1,870 | 214 | 14,500 | -6,990 |

[a] NM = not measured.

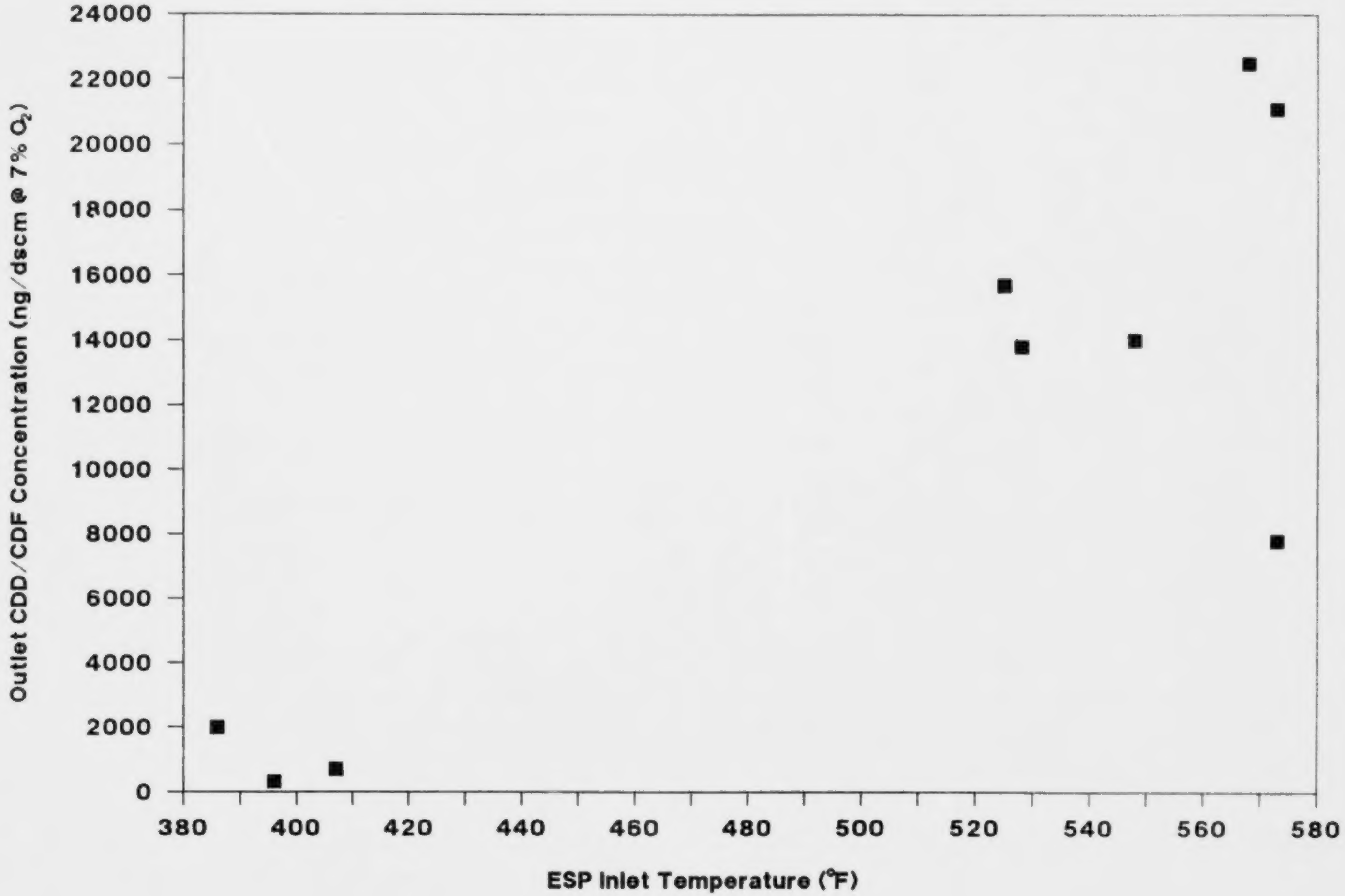


Figure 2-3. Outlet CDD/CDF concentration as a function of ESP inlet temperature at Dayton.

The test runs at Dayton at ESP inlet temperature setpoints of 400 and 525°F showed an 81 to 98 percent decrease in CDD/CDF concentrations from the mixing chamber to the ESP inlet. CDD/CDF was not measured at the mixing chamber during the 575°F runs. At 400°F, the CDD/CDF concentrations decreased by up to 71 percent from the mixing chamber to the ESP outlet. At 525°F, the ESP outlet CDD/CDF concentrations were greater than at the mixing chamber. This suggests that the ESP provides surface area and residence time for CDD/CDF formation, with the amount of formation at least partially dependent on the temperature.

Inlet CDD/CDF may affect outlet CDD/CDF concentration, as shown in Figure 2-4. At ESP inlet concentrations of 10 to 50 ng/dscm, emissions of 320 to 1,990 ng/dscm resulted. At ESP inlet concentrations of 150 to 390 ng/dscm, CDD/CDF emissions of 13,800 to 22,500 ng/dscm resulted with the exception of Run 1. Run 1 had an outlet CDD/CDF concentration of 7,790 ng/dscm and an inlet concentration of 254 ng/dscm. However, as discussed previously, this observation may actually be a result of inlet temperature. At a given temperature, neither the outlet CDD/CDF concentrations nor the degree of CDD/CDF formation change with the inlet CDD/CDF concentration.

2.2.1.5 McKay Bay.[11-13] The McKay Bay Refuse-to-Energy Facility in Tampa, Florida, consists of four identical process lines each designed to combust 250 tons/day of MSW. The combustors are Volund refractory units which use drying and ignition grates followed by a rotary kiln. Emissions from each combustor are controlled by a F. L. Smidth 2-field ESP, each with an SCA of 445 $ft^2$/1,000 acfm and design PM removal efficiency of 99.45 percent. At the ESP inlet, the flue gas flow is typically about 83,000 acfm (38,000 dscfm) at a temperature of about 565°F. Treated flue gas is released through two stacks (two process lines per stack).

A compliance test was conducted at the facility in September 1985. The facility was operating at normal combustor and ESP conditions. During the test program, three runs were conducted at each unit, with PM, $SO_2$, HF, THC, $NO_x$, mercury, lead, and beryllium emissions measured at the ESP outlet.

Particulate data from the test are reported in Table 2-8. The average outlet PM concentrations for each of the units were 0.013, 0.012, 0.0042, and 0.0079 gr/dscf. No inlet PM data were collected.

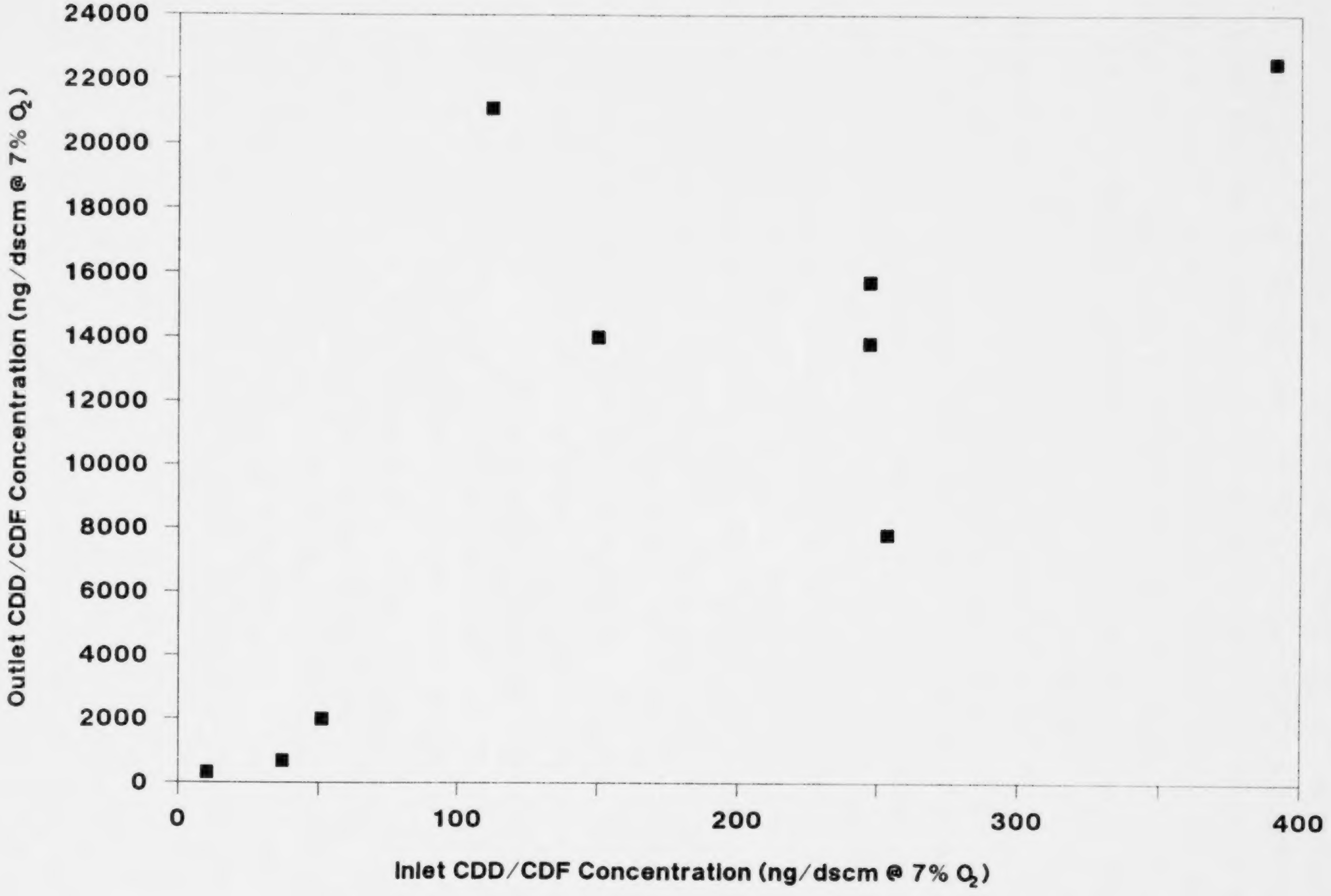


Figure 2-4. Outlet CDD/CDF concentration as a function of inlet CDD/CDF concentration at Dayton.

TABLE 2-8. PARTICULATE AND METALS EMISSIONS DATA FOR McKAY BAY

| Test Condition | Run Number[a] | ESP Inlet Temperature[b] (°F) | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug dscm at 7% $O_2$) | |
|---|---|---|---|---|---|---|
| | | | | | Pb | Hg |
| Combustor = Normal | 1-7 | 536 | 82,000 | 0.015 | 1,630 | 573 |
| ESP = Normal | 1-8 | 553 | 86,700 | 0.013 | 763 | 452 |
| | 1-9 | 564 | 89,400 | 0.010 | 808 | 1,000 |
| Average (Unit 1) | | 551 | 86,000 | 0.013 | 1,070 | 675 |
| | 2-7 | 552 | 82,400 | 0.012 | 1,240 | 1,280 |
| | 2-8 | 570 | 82,700 | 0.012 | 1,140 | 522 |
| | 2-9 | 570 | 82,500 | 0.011 | 1,040 | 913 |
| Average (Unit 2) | | 564 | 82,500 | 0.012 | 1,140 | 905 |
| | 3-7 | 558 | 77,300 | 0.0040 | 887 | 1,220 |
| | 3-8 | 557 | 77,300 | 0.0049 | 885 | 1,020 |
| | 3-9 | 564 | 77,300 | 0.0036 | 1,020 | 676 |
| Average (Unit 3) | | 560 | 77,300 | 0.0042 | 931 | 972 |
| | 4-7 | 554 | 91,200 | 0.012 | 1,190 | 1,710 |
| | 4-8 | 545 | 90,100 | 0.0024 | 1,050 | 672 |
| | 4-9 | 536 | 84,600 | 0.0094 | 1,450 | 1,024 |
| Average (Unit 4) | | 545 | 88,600 | 0.0079 | 1,230 | 1,135 |

[a] Run Number contains unit number followed by run number on that unit.

[b] ESP inlet temperature estimated from measured temperature at ESP outlet and an estimated temperature drop based on previously measured values (6°F for Unit 1, 30°F for Unit 2, 12°F for Unit 3, 8°F for Unit 4).

Lead and mercury emissions at McKay Bay, presented in Table 2-8, averaged 1,090 and 922 ug/dscm at 7 percent $O_2$, respectively. Based on typical uncontrolled metals concentrations (Section 1.2), lead was removed at 97 percent efficiency. Mercury was apparently not removed by the ESP since the outlet concentration was within the range of typical uncontrolled mercury emission concentrations (248 to 1,030 ug/dscm).

2.2.1.6 North Andover.[15] The North Andover, Massachusetts, facility consists of two identical mass burn, waterwall combustors each designed to combust 750 tons/day of MSW on Martin reciprocating grates. The air pollution control system consists of two identical Wheelabrator ESP's with 3 fields, each designed to reduce PM to 0.05 gr/dscf at 12 percent $CO_2$, which corresponds to a design collection efficiency of 98 percent. Specific collecting area and other design data for the ESP's are considered confidential by the ESP manufacturer and are therefore not available. At the ESP inlet, the flue gas flow is about 210,000 acfm at a temperature of 590 to $600^0$F.

In July 1986, compliance testing was conducted at the North Andover MWC. Concurrent with the compliance testing, a test program to measure pollutant levels at the ESP inlet was undertaken to quantify performance of the ESP. At the ESP inlet and outlet, PM, metals, and CDD/CDF were sampled. Inlet PM was sampled only during Runs 8 and 9. Inlet CDD/CDF samples for Runs 1 and 2 were not analyzed because of sampling problems. Because the metals analyses were performed using an uncertified method, the data are suspect and are not included in this report.

Particulate data from the testing at North Andover are presented in Table 2-9. Outlet PM concentrations for six runs were between 0.0018 and 0.0054 gr/dscf at 12 percent $CO_2$ and averaged 0.0036 gr/dscf. Greater than 99 percent removal of PM occurred during the two runs in which it was measured. Because the ESP collection area is unknown, the SCA of the ESP cannot be calculated.

Test data for CDD/CDF emission measurements are presented in Table 2-10. Simultaneous inlet and outlet measurements were conducted on three runs and outlet measurements only on the additional runs. During each of the

## TABLE 2-9. PARTICULATE DATA FOR NORTH ANDOVER

| Test Condition | Run Number | ESP Inlet Temperature ($^{o}$F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal<br>ESP = Normal | 2 | 615 | 218,500 | NM[a] | 0.0050 | - |
| | 3 | 580 | 195,300 | NM | 0.0013 | - |
| | 4 | 584 | 201,000 | NM | 0.0032 | - |
| | 5 | 591 | 207,800 | NM | 0.0023 | - |
| | 8 | 600 | 221,500 | 0.737 | 0.0044 | 99.5 |
| | 9 | 609 | 219,300 | 0.922 | 0.0054 | 99.4 |
| Average | | 597 | 210,600 | 0.830 | 0.0036 | 99.5 |

[a] NM = Not measured.

TABLE 2-10. CDD/CDF DATA FOR NORTH ANDOVER

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (%) |
|---|---|---|---|---|---|
| Combustor = Normal<br>ESP = Normal | 1 | 607 | NM[a] | 396 | - |
|  | 2 | 615 | NM | 384 | - |
|  | 3 | 580 | 397 | 524 | -31.8 |
|  | 4 | 584 | 139 | 204 | -46.4 |
|  | 5 | 591 | 200 | 302 | -51.0 |
| Average |  | 595 | 245 | 362 | -43.1 |

[a] NM = Not measured.

of the three runs for which both inlet and outlet CDD/CDF concentrations were measured, CDD/CDF concentrations were higher at the ESP outlet than at the inlet. The ESP inlet concentrations ranged from 139 to 397 ng/dscm and the corresponding outlet concentrations ranged from 204 to 524 ng/dcsm. The inlet concentration averaged 245 ng/dscm while the outlet concentrations averaged 362 ng/dscm. The average CDD/CDF removal efficiency was -43 percent. The ESP inlet temperature during these tests averaged nearly 600°F, which is well within the suggested range for CDD/CDF formation.

The data suggest that there may be an effect of inlet CDD/CDF concentration on CDD/CDF removal efficiency. At the highest inlet concentration, 397 ng/dscm, the smallest relative increase in CDD/CDF concentration occurred. Lower inlet CDD/CDF concentrations yielded higher relative increases in CDD/CDF concentrations across the ESP.

Plotted in Figure 2-5 is inlet CDD/CDF concentration versus outlet CDD/CDF concentration. Although limited to only three data points, these three points suggest that there exists a relatively strong relationship between inlet CDD/CDF concentration and CDD/CDF formation at temperatures approaching 600°F.

2.2.1.7 Peekskill.[16,17] The Westchester RESCO facility in Peekskill, New York, consists of three identical waterwall combustors with Von Roll reciprocating grates. Each unit has a design capacity of 750 tons of refuse per day. Emissions from each combustor are controlled by a 3-field, wire and plate ESP built by Wheelabrator Air Pollution Control in 1984. Each ESP has a design SCA of 428 $ft^2$/1,000 acfm (flue gas flow of 175,900 acfm) with a superficial velocity of 3.55 ft/sec. The design flue gas temperature at the ESP inlet was 425°F, but the system typically operates at about 455°F. The ESP outlet temperature is typically about 435°F. Each ESP is designed to achieve a PM removal efficiency of 99 percent.

Two separate test campaigns have been conducted at the Peekskill facility. In April 1985, sampling was conducted as part of the New York State Department of Environmental Conservation's program to assess the health effects of municipal waste combustion. At the ESP outlet, flue gas was

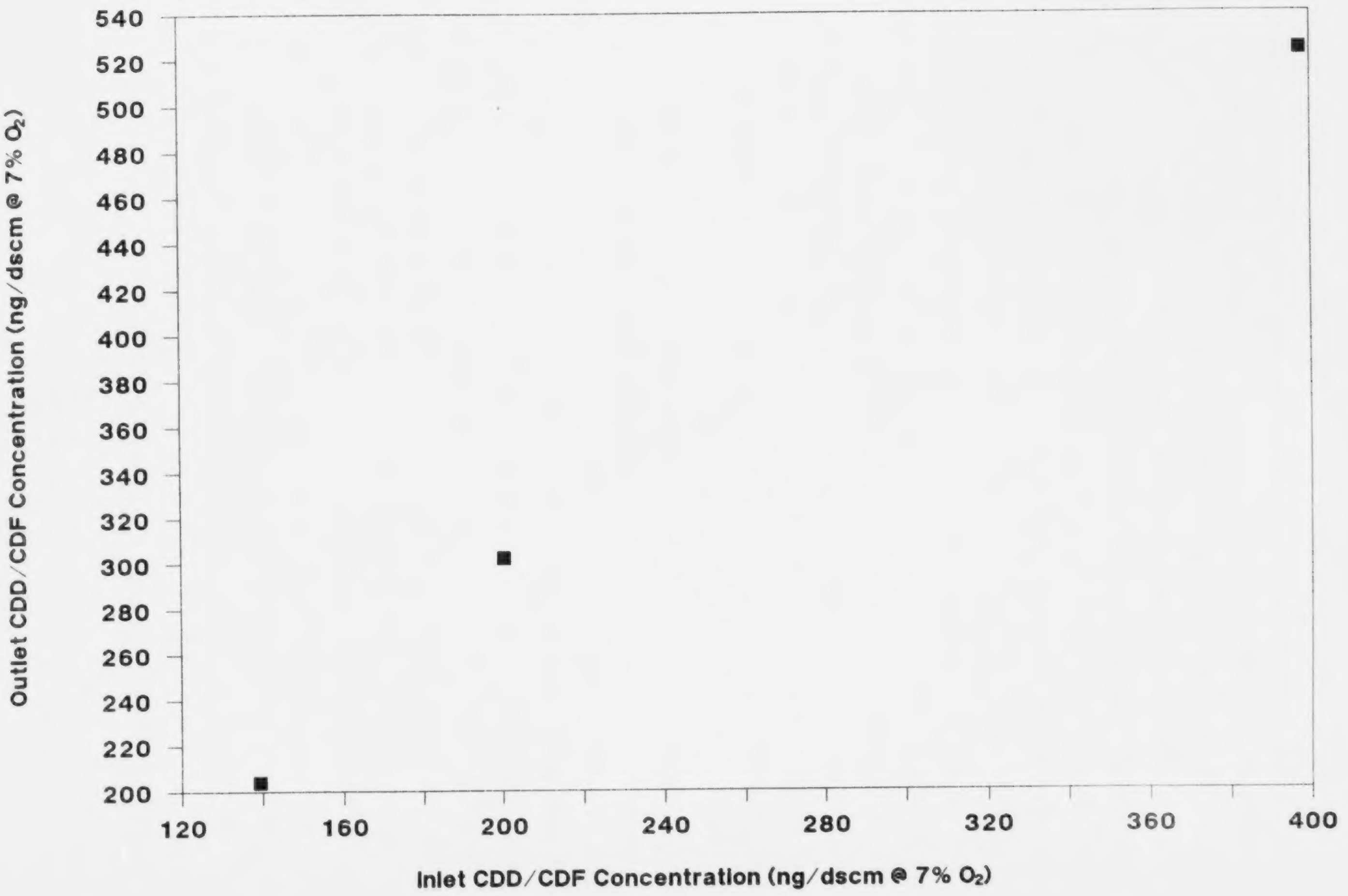


Figure 2-5. Outlet CDD/CDF concentration as a function of inlet CDD/CDF concentration at the North Andover MWC.

sampled for CDD/CDF, PM, HCl, $SO_2$, $NO_x$, metals (arsenic, beryllium, mercury, cadmium, chromium, lead, manganese, nickel, vanadium, and zinc), and other organics. The PM and some of the metals results from this test campaign have been invalidated because of a problem with systematic contamination of the collected samples. Specifically, extremely high PM levels were measured. This suggests that the samples may have been contaminated by material that was dislodged from the inside of the test ports. Except for arsenic, beryllium, and mercury, which were collected separate from the PM sample, the results for other metals are also considered suspect due to the contamination problem and are thus not reported here.

In November 1985, extensive sampling was conducted under various parametric combustor conditions and normal ESP conditions. Tests were conducted under five different operating conditions: (1) normal load, end of campaign (dirty heat transfer surfaces); (2) start-up (transient conditions); (3) normal load, start of campaign (clean heat transfer surfaces); (4) high load (115 percent of design); (5) low load (85 percent of design). Triplicate sample runs were performed for each test condition except for start-up, where only two sample runs were performed. The first start-up test was performed following a 7-day maintenance outage after the end of campaign tests. The second start-up test was performed several months later. The pollutants measured include CDD/CDF, PM, $SO_2$, HCl, and $NO_x$, and other organics. Flue gas was simultaneously sampled at the boiler inlet, ESP inlet, and ESP outlet. The CDD/CDF samples were not collected simultaneously with the PM or HCl samples, but were taken under similar combustor operating conditions. Measurements of $SO_2$ and $NO_x$ were collected by CEM. Generally these data were taken simultaneously with both the CDD/CDF and PM samples. During the start-up runs, only CDD/CDF samples were collected.

Particulate data from the November test program are presented in Table 2-11. Twelve simultaneous inlet and outlet sample runs were conducted under varying combustor conditions but normal ESP conditions. Inlet PM concentrations ranged from 0.28 gr/dscf (Run 6) to 2.7 gr/dscf (Run 8). The outlet PM concentrations ranged from 0.0083 to 0.036 gr/dscf (Run 3) at 12 percent $CO_2$, and averaged 0.017 gr/dscf. Excluding Run 6, removal efficiencies for PM ranged from 97.1 to 99.5 percent and averaged 98.8 percent.

TABLE 2-11. PARTICULATE DATA FOR PEEKSKILL

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal load, | 1 | 461 | 181,200 | 1.68 | 0.0083 | 99.5 |
| end of campaign[a] | 2 | 472 | 200,300 | 1.53 | 0.016 | 98.9 |
| ESP = Normal | 3 | 479 | 198,000 | 1.68 | 0.036 | 97.9 |
| Average | | 471 | 193,200 | 1.63 | 0.020 | 98.8 |
| Combustor = Normal load, | 5 | 457 | 202,400 | 2.11 | 0.016 | 99.2 |
| start of campaign[a] | 6 | 459 | 204,000 | 0.28 | 0.018 | 93.2 |
| ESP = Normal | 7 | 446 | 180,700 | 2.12 | 0.011 | 99.5 |
| Average | | 454 | 195,700 | 2.12[b] | 0.015 | 99.4[b] |
| Combustor = High load[a] | 8 | 462 | 210,700 | 2.70 | 0.015 | 99.4 |
| ESP = Normal | 9 | 464 | 201,300 | 1.89 | 0.011 | 99.4 |
| | 10 | 462 | 207,000 | 1.72 | 0.019 | 98.9 |
| Average | | 463 | 206,300 | 2.10 | 0.015 | 99.2 |
| Combustor = Low load[a] | 11 | 436 | 172,400 | 0.91 | 0.019 | 98.0 |
| ESP = Normal | 12 | 436 | 165,600 | 0.66 | 0.019 | 97.1 |
| | 13 | 418 | 150,400 | 1.33 | 0.0087 | 99.3 |
| Average | | 430 | 162,800 | 0.97 | 0.016 | 98.1[b] |

[a] November 1985 testing.

[b] Average excludes Run 6 due to low measured inlet PM concentration.

Analysis of the effect of SCA on PM removal efficiency showed no significant trend. This is likely due to the relatively narrow variation around the design SCA encountered during the test program.

Analysis of the effect of inlet PM on outlet PM emissions at Peekskill showed that outlet PM concentrations were relatively insensitive to inlet PM concentration. Except for one run, outlet PM concentrations ranged narrowly from about 0.01 to 0.02 gr/dscf at 12 percent $CO_2$ over a wide range of inlet PM concentration (0.3 to 2.7 gr/dscf). In no case did the average outlet PM emissions from each test condition exceed 0.02 gr/dscf. As shown in Figure 2-6, PM removal efficiency tended to increase with inlet PM concentration at Peekskill.

Results for mercury and arsenic from the testing in April are presented in Table 2-12. Emissions of mercury and arsenic averaged 1,790 and 2.17 ug/dscm at 7 percent $O_2$, respectively. The mercury emissions compared to typical uncontrolled mercury concentrations (see Section 1.2.) suggest that no mercury removal occurred. In contrast, the arsenic emissions suggest that a removal efficiency of 99 percent was achieved.

The CDD/CDF data from the April and November, 1985 tests are presented in Table 2-13. Concentrations of CDD/CDF during normal and high load combustion conditions (Runs 1-3 and 5-10) ranged from 333 to 861 ng/dscm at 7 percent $O_2$ at the ESP inlet and 82 to 297 ng/dscm at 7 percent $O_2$ at the ESP outlet. Removal efficiencies ranged from 37 to 80 percent and averaged 63 percent. During the low load tests (Runs 11-13), CDD/CDF concentrations were 132 to 281 ng/dscm at the ESP inlet and 96 to 250 ng/dscm at the ESP outlet. Removal efficiencies during these tests ranged from 11 to 64 percent and averaged 34 percent. During start-up tests (Runs 4 and 14), CDD/CDF concentrations were near 10,000 ng/dscm at both the ESP inlet and outlet. Removal efficiencies during the two start-up tests were 11 and 20 percent. Of the ESP's in the database for which both inlet and outlet CDD/CDF measurements are available, only the ESP at Peekskill achieved a positive CDD/CDF removal efficiency. Data for the other ESP's in the database show higher outlet CDD/CDF concentrations than inlet concentrations.

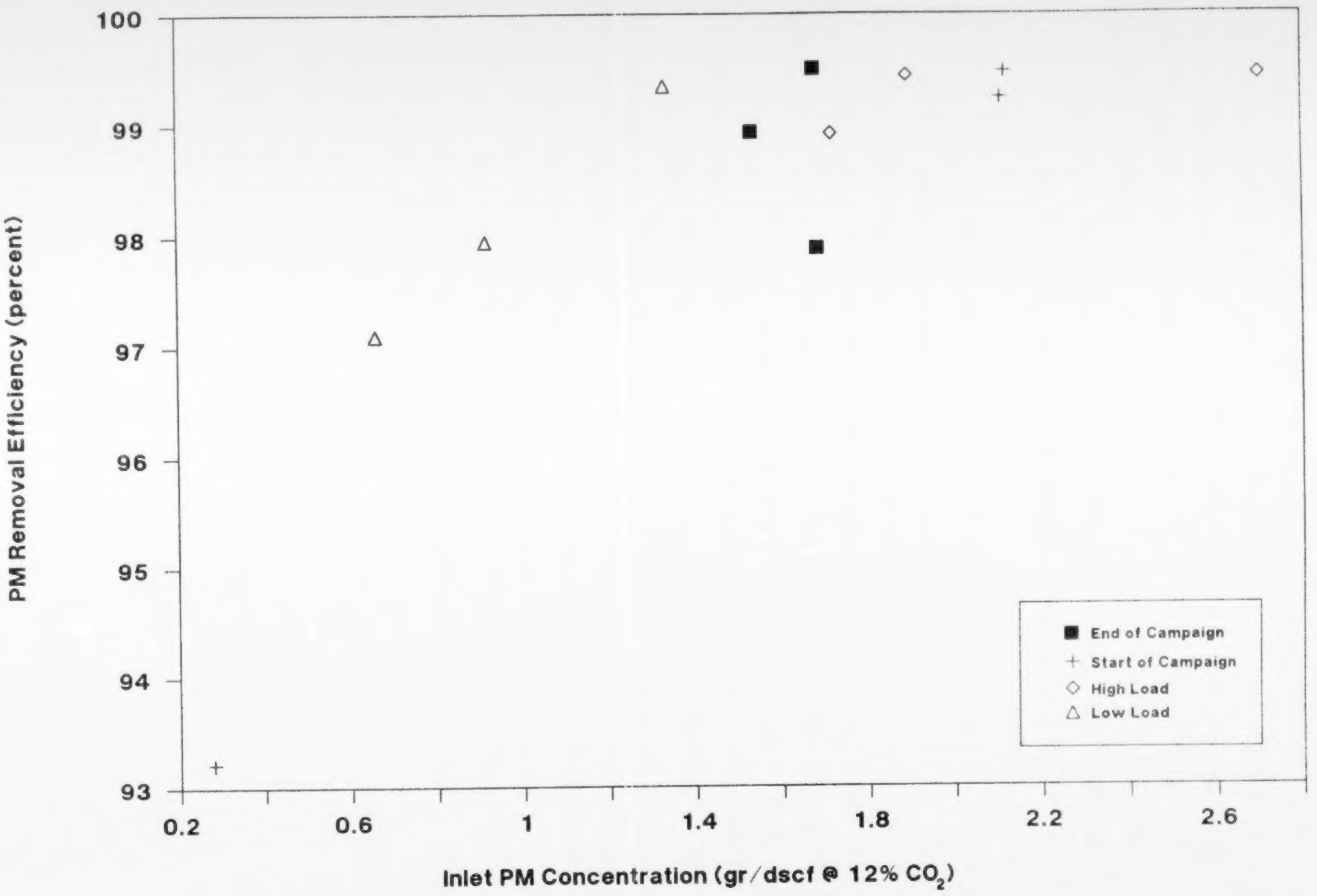


Figure 2-6. PM removal efficiency as a function of inlet PM concentration at the Peekskill MWC.

## TABLE 2-12. METALS EMISSIONS DATA FOR PEEKSKILL

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration[a] (ug/dscm at 7% $O_2$) As | Outlet Concentration[a] (ug/dscm at 7% $O_2$) Hg |
|---|---|---|---|---|---|
| Combustor = Normal[b] | 1 | NM[c] | -- | 2.33 | 1,320 |
| ESP = Normal | 2 | NM | -- | 2.05 | 1,510 |
| | 3 | NM | -- | 2.14 | 2,540 |
| Average | | 458[d] | 0.017[e] | 2.17 | 1,790 |

[a] Particulate samples were analyzed for Cd, Cr, Pb, and Ni, but the results are suspect and are not reported here.

[b] Metals results from April 1985 testing.

[c] NM = Not measured.

[d] Temperature assumed same as for November 1985 testing.

[e] Average PM results from November 1985 testing. Particulate samples from April were invalidated because of systematic contamination.

## TABLE 2-13. CDD/CDF DATA FOR PEEKSKILL

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (%) |
|---|---|---|---|---|---|
| Combustor = Normal[a] | 1 | 458[b] | - | 85.8 | - |
| ESP = Normal | 2 | 458[b] | - | 98.2 | - |
| | 3 | 458[b] | - | 138 | - |
| Average | | 458[b] | - | 107 | - |
| Combustor = Normal load, | 1 | 472 | 584 | 222 | 62.0 |
| end of campaign[c] | 2 | 471 | 411 | 143 | 65.1 |
| ESP = Normal | 3 | 471 | 861 | 173 | 79.9 |
| Average | | 471 | 617 | 179 | 69.0 |
| Combustor = Normal load, | 5 | 444 | 473 | 297 | 37.3 |
| start of campaign[c] | 6 | 445 | 525 | 224 | 57.4 |
| ESP = Normal | 7 | 447 | 436 | 267 | 38.8 |
| Average | | 445 | 478 | 263 | 44.5 |
| Combustor = High load[c] | 8 | 461 | 566 | 169 | 70.1 |
| ESP = Normal | 9 | 460 | 416 | 127 | 69.5 |
| | 10 | 441 | 333 | 81.9 | 75.4 |
| Average | | 454 | 438 | 126 | 71.7 |
| Combustor = Low load[c] | 11 | 437 | 271 | 97.7 | 63.9 |
| ESP = Normal | 12 | 437 | 281 | 250 | 11.0 |
| | 13 | 436 | 132 | 95.6 | 27.4 |
| Average | | 437 | 228 | 148 | 34.1 |
| Combustor = Start-up[c] | 4 | 383 | 13,782 | 11,080 | 19.6 |
| ESP = Normal | 14 | 455 | 9,082[d] | 8,060[d] | 11.2 |
| Average | | 419 | 11,432 | 9,570 | 15.4 |

[a] April 1985 testing.

[b] ESP inlet temperature not measured during April 1985 test. Assumed to equal average from November 1985 normal load tests (start and end of campaign).

[c] November 1985 testing.

[d] Includes mono- through octa- CDD/CDF.

Flue gas temperatures at the ESP inlet during all of these tests (excluding Run 4) were between 436 and 472°F. These ESP inlet temperatures are at the lower end of the range where CDD/CDF formation across an ESP has been suggested to occur. However, because of the narrow range in ESP operating temperature during these tests, it is not possible to evaluate a correlation between temperature and ESP performance, even though there are 12 simultaneous measurements of CDD/CDF at the ESP inlet and outlet.

In Figure 2-7, CDD/CDF removal efficiency (excluding start-up tests) is plotted as a function of inlet CDD/CDF concentration. As the plot indicates, there does not appear to be a strong relationship between removal efficiency and inlet CDD/CDF concentration.

2.2.1.8 Pinellas County.[18] The Pinellas County Resource Recovery Facility in St. Petersburg, Florida, includes three identical mass burn waterwall combustors. The combustors have Martin reciprocating grates and each is designed to combust 1,000 tons/day of MSW. Emissions are controlled by 3-field rigid wire and plate ESP's built by Wheelabrator Air Pollution Control. The SCA of the ESP's is considered confidential by the ESP manufacturer and is not available. At the ESP inlet, the flue gas flow is typically 270,000 acfm at a temperature of 540°F. The controlled emissions are discharged through individual stacks.

Compliance tests were conducted at Unit 3 of the facility in February 1987. The combustor and ESP were under normal operating conditions during the tests. Simultaneous ESP inlet and outlet measurements were made for PM and CDD/CDF. Additional measurements were collected at the ESP outlet for $NO_x$, $SO_2$, HCl, HF, mercury, beryllium, arsenic, hexavalent chromium, and organics including benzene, chlorobenzene, chlorophenol, PAH's, PCB's, and PCP's.

Particulate data from the three sample runs conducted are presented in Table 2-14. Outlet concentrations ranged from 0.0018 to 0.0026 gr/dscf at 12 percent $CO_2$ and averaged 0.0023 gr/dscf. The removal efficiency exceeded 99.7 percent for all three runs.

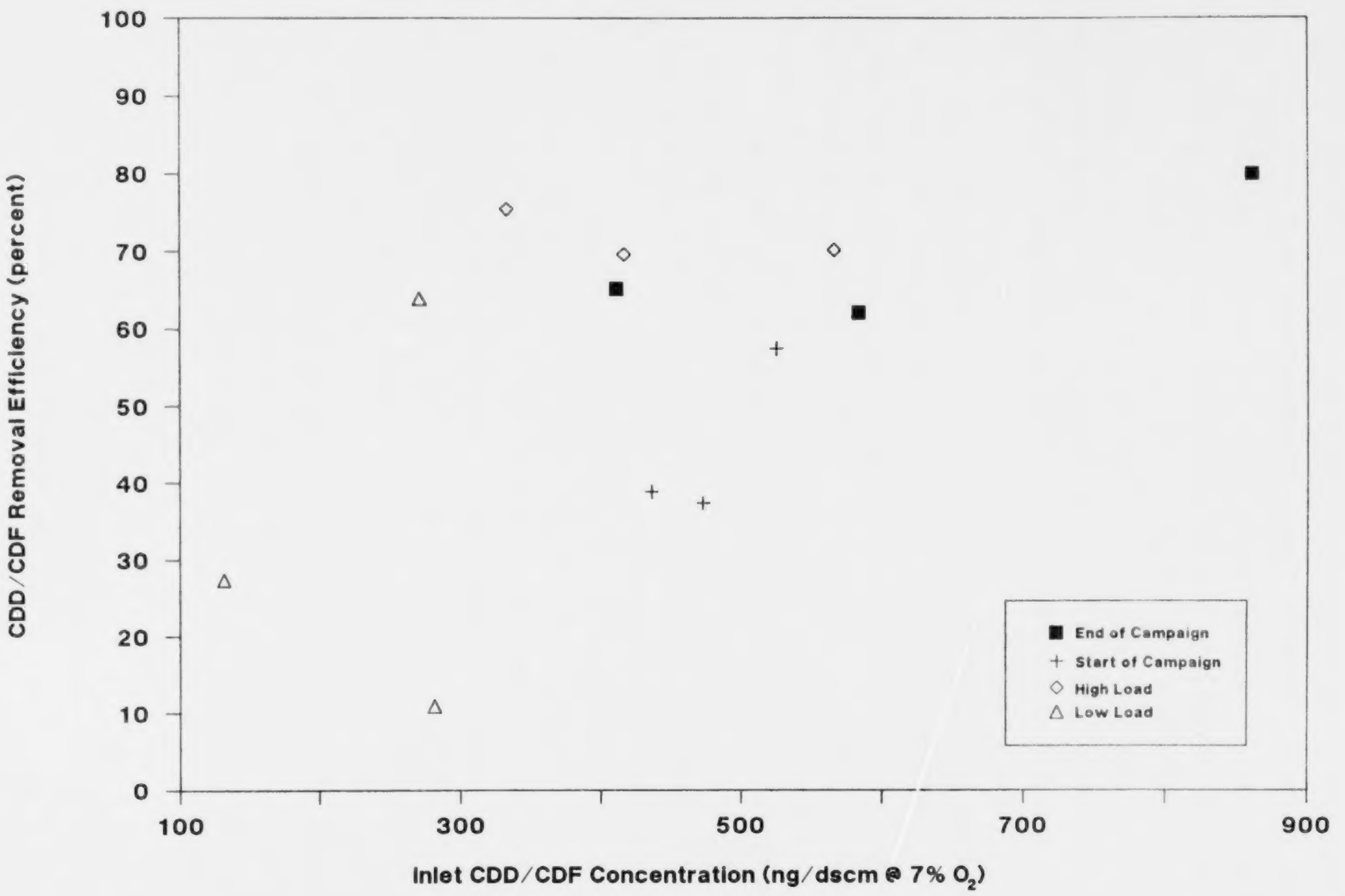


Figure 2-7. CDD/CDF removal efficiency as a function of inlet CDD/CDF concentration at the Peekskill MWC.

## TABLE 2-14. PARTICULATE DATA FOR PINELLAS COUNTY

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal | 1 | 514 | 259,000 | 1.16 | 0.0024 | 99.8 |
| ESP = Normal | 2 | 527 | 271,000 | 0.838 | 0.0018 | 99.8 |
|  | 3 | 537 | 271,400 | 0.881 | 0.0026 | 99.7 |
| Average |  | 526 | 267,100 | 0.960 | 0.0023 | 99.8 |

Metals data from three runs conducted at the ESP outlet are summarized in Table 2-15. A comparison of the outlet data with typical uncontrolled concentrations (see Section 1.2) for arsenic, cadmium, chromium, lead, and nickel suggest that the ESP is achieving a relatively high level of removal (greater than 98 percent) for these metals. For mercury, however, the outlet concentration suggests that little or no removal is achieved.

CDD/CDF results from the six test runs conducted at the ESP inlet and outlet at from Pinellas County are presented in Table 2-16. Inlet CDD/CDF concentrations mesured during the six runs ranged from 31 to 103 ng/dscm and averaged 54 ng/dscm. These concentrations are unusually low for any combustor type and suggest that good combustion generates little CDD/CDF. Outlet CDD/CDF concentrations ranged from 50 to 163 ng/dscm and averaged 100 ng/dscm. For each sample run, the outlet CDD/CDF concentration was higher than that measured at the inlet. The ESP was operating at 524 to $552^{0}$F during the test, which is within the temperature range suggested for CDD/CDF formation.

Figure 2-8 is a plot of outlet CDD/CDF concentration as a function of inlet CDD/CDF concentration. Increasing inlet concentration appears to increase outlet CDD/CDF concentrations. A plot of relative CDD/CDF formation (negative removal efficiency) as a function of inlet CDD/CDF concentration is shown in Figure 2-9. This plot shows no causal relationship between the two variables. Because PM and CDD/CDF were not measured simultaneously, the effect of inlet PM on CDD/CDF formation or outlet emissions cannot be evaluated.

2.2.1.9 Quebec City.[19] The Quebec City, Canada, MSW facility contains four separate waterwall combustors. These were originally built in 1974 and 1975 with Von Roll reciprocating grates. Waterwall arches were added to the combustor chambers in 1979. One unit was further modified in 1985/1986 to include a "bull nose" in the combustion chamber and a modified secondary air flow. Each unit is designed to combust 250 tons/day of MSW. Emissions are controlled by 2-field ESP's which then exit through a common stack for all four lines. The SCA of the ESP is unavailable, but the ESP is designed to achieve 98.5 percent PM removal. The design flue gas flow at the ESP inlet is 100,000 acfm at a temperature of $540^{0}$F.

## TABLE 2-15. METALS EMISSIONS DATA FOR PINELLAS COUNTY

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal | 1 | 539 | 0.0024 | 3.61 | 9.03 | 1.08 | 123 | 1,102 | 1.08 |
| ESP = Normal | 2 | 541 | 0.0018 | 4.57 | 7.27 | 10.6 | 230 | 892 | 6.06 |
| | 3 | 549 | 0.0026 | 2.33 | 6.90 | 0.86 | 105 | 547 | ND[a] |
| Average | | 543 | 0.0023 | 3.50 | 7.73 | 4.18 | 153 | 847 | 2.38 |

[a] ND = Not detected. Considered as zero in evaluating averages.

## TABLE 2-16. CDD/CDF DATA FOR PINELLAS COUNTY

| Test Condition | Run Number | ESP Inlet Temperature ($^{o}$F) | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (%) |
|---|---|---|---|---|---|
| Combustor = Normal | 1 | 552 | 103 | 163 | - 58 |
| ESP = Normal | 2 | 524 | 35 | 79 | -127 |
| | 3 | 536 | 43 | 127 | -194 |
| | 4 | 546 | 46 | 82 | - 80 |
| | 5 | 523 | 31 | 50 | - 62 |
| | 6 | 539 | 65 | 97 | - 50 |
| Average | | 537 | 54 | 100 | - 95 |

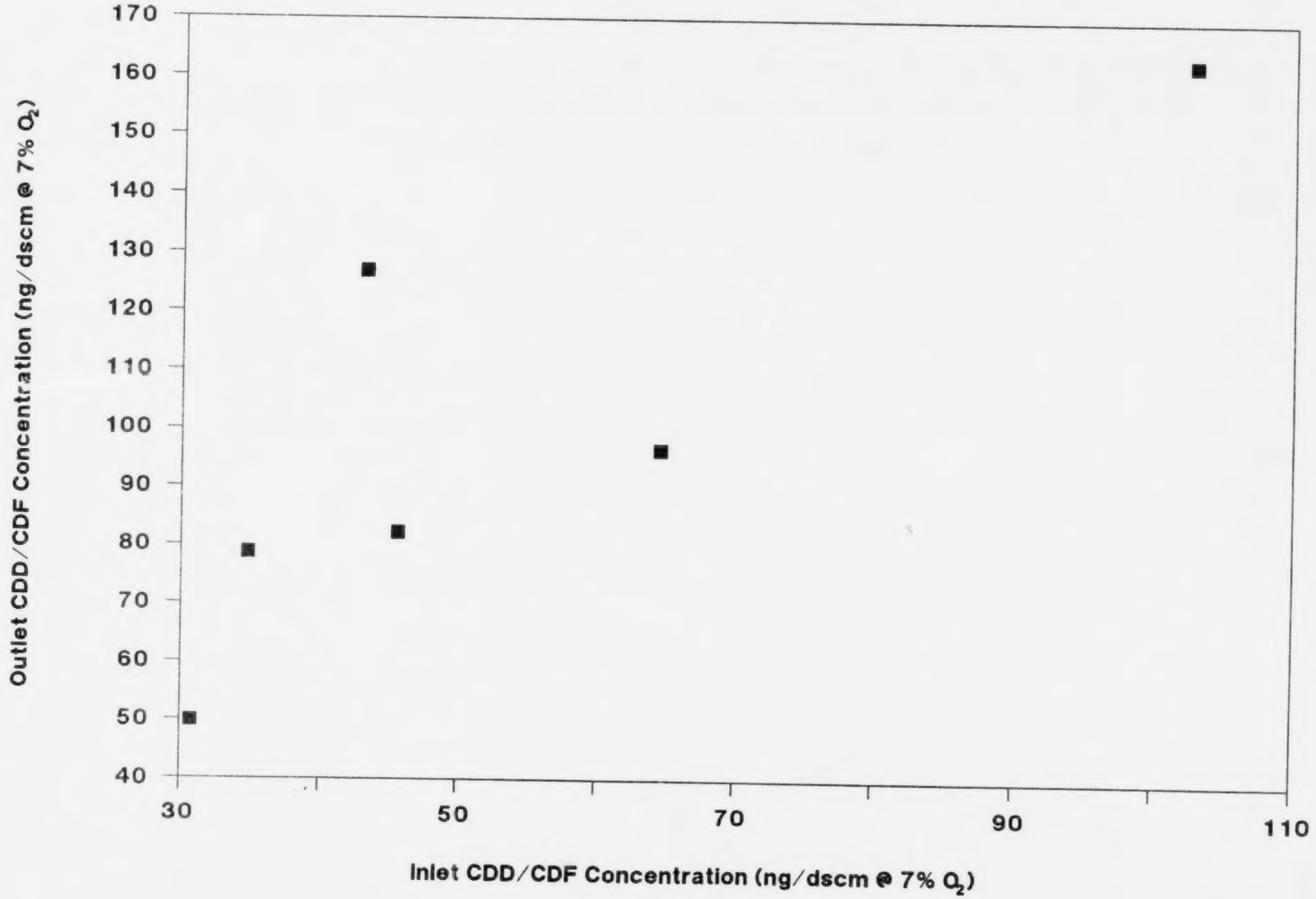


Figure 2-8. Outlet CDD/CDF concentration as a function of inlet CDD/CDF concentration at the Pinellas County MWC.

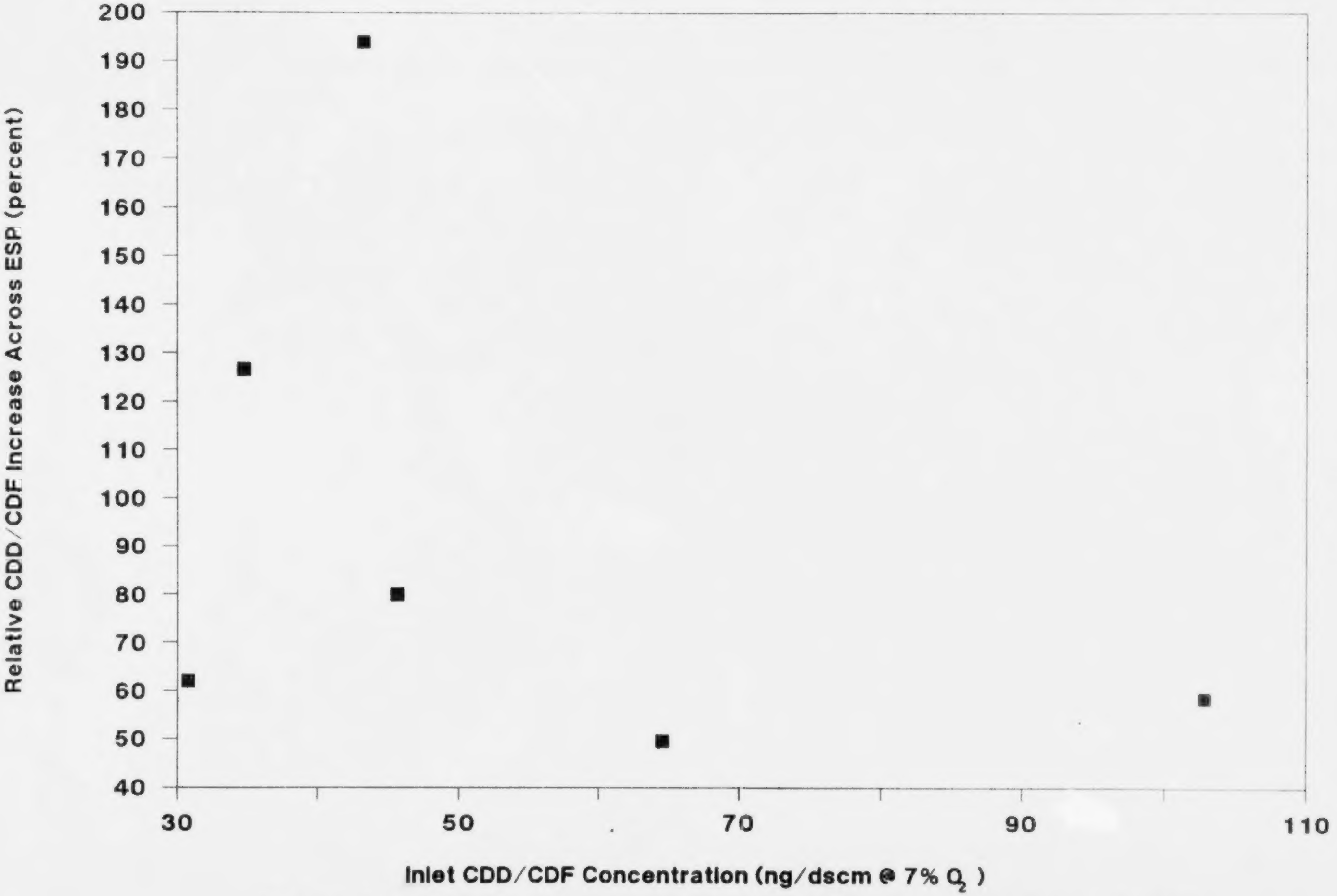


Figure 2-9. Relative increase of CDD/CDF across ESP as a function of inlet CDD/CDF concentration at the Pinellas County MWC.

From May through June 1986, testing was conducted on the modified combustor. The test program was designed to collect process and emissions data over a range of different combustor operating conditions in order to relate combustor operating conditions with emissions of metals and organics, ash quality, and boiler efficiency. The process parameters were varied to yield five distinct operating conditions: (1) low feed rate (70 percent of design), good combustion conditions; (2) design feed rate, good combustion conditions; (3) high feed rate (115 percent of design) good combustion conditions; (4) design feed rate, low combustor temperature; and (5) design feed rate, poor air distribution. The ESP was kept at normal operating conditions throughout the test program. Flue gas was sampled at the ESP outlet and analyzed for CDD, CDF, PCB's, PAH, chlorinated benzene, chlorinated phenol, PM, $SO_2$, HCl, THC, $NO_x$, and metals (including arsenic, cadmium, chromium, lead, mercury, and nickel). Additional testing at this combustor using pilot-scale spray drying and dry sorbent injection systems with a fabric filter was conducted in March 1985. Results of this test program are presented in Sections 5.2 and 7.2, respectively.

Particulate data from Quebec City are presented in Table 2-17. Outlet particulate concentrations for 14 sample runs ranged from 0.009 to 0.032 gr/dscf and averaged 0.018 gr/dscf at 12 percent $CO_2$.

Metals data collected at Quebec City are presented in Table 2-18. Test results are not available for the individual runs, but are summarized by test condition. Uncontrolled metals concentrations were not measured during this test. However, when compared with typical uncontrolled values presented in Section 1.2, removal efficiencies for chromium and nickel could be as high as 99 percent; cadmium and arsenic slightly less, around 97 percent; and lead about 95 percent. The outlet mercury concentration would suggest that little or no mercury control was achieved.

CDD/CDF data from Quebec City are presented in Table 2-19. Outlet data are available for 13 sample runs conducted under the combustor conditions described above and normal ESP operation. No inlet data were collected. Outlet CDD/CDF concentrations ranged from 46 to 690 ng/dscm and averaged 370 ng/dscm at 7 percent $O_2$.

TABLE 2-17. PARTICULATE DATA FOR QUEBEC CITY

| Test Condition | Run Number | ESP Inlet Temperature (°F)[a] | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Low feed rate, good combustion; ESP = Normal | 2 | 410 | 57,400 | 0.011 |
| | 10 | 434 | 60,400 | 0.013 |
| | 11 | 434 | 58,000 | 0.012 |
| Average | | 426 | 58,600 | 0.012 |
| Combustor = Design feed rate, good combustion; ESP = Normal | 5 | 423 | 56,800 | 0.007 |
| | 6 | 434 | 59,000 | 0.009 |
| | 12 | 457 | 57,000 | 0.014 |
| Average | | 438 | 57,600 | 0.010 |
| Combustor = High feed rate, good combustion; ESP = Normal | 7 | 448 | 65,100 | 0.016 |
| | 9 | 471 | 71,600 | 0.016 |
| | 13 | 484 | 75,500 | 0.024 |
| Average | | 468 | 70,700 | 0.019 |
| Combustor = Design feed rate, low comb. temp.; ESP = Normal | 3 | 464 | 79,600 | 0.030 |
| | 4 | 470 | 81,000 | 0.019 |
| Average | | 467 | 80,300 | 0.025 |
| Combustor = Design feed rate, poor air dist.; ESP = Normal | 14 | 470 | 73,400 | 0.032 |
| | 15 | 462 | 73,500 | 0.023 |
| Average | | 466 | 73,500 | 0.028 |

[a] Estimated from measured temperature at ESP outlet and an assumed temperature drop across the ESP (25°F).

TABLE 2-18. METALS EMISSIONS DATA FOR QUEBEC CITY

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Low Feed Rate, Good Combustion; ESP = Normal | 2,10,11[a] | 406 | 0.012 | 1.8 | 31.0 | 12.4 | 1,147 | 918 | 10.4 |
| Combustor = Design Feed Rate, Good Combustion; ESP = Normal | 5,6,12[a] | 417 | 0.0099 | 2.7 | 23.4 | 7.2 | 655 | 685 | 5.1 |
| Combustor = High Feed Rate, Good Combustion; ESP = Normal | 7,9[a] | 439 | 0.016 | 4.8 | 43.1 | 15.7 | 1,699 | 927 | 8.5 |
| Combustor = Design Feed Rate, Low Comb. Temp; ESP = Normal | 3,4[a] | 448 | 0.024 | 6.8 | 93.3 | 21.4 | 2,123 | 843 | 8.3 |
| Combustor = Design Feed Rate, Poor Air Dist.; ESP = Normal | 14,15[a] | 446 | 0.028 | 6.7 | 79.7 | 15.2 | 2,627 | 655 | 7.0 |
| Average | | 431 | 0.018 | 4.6 | 54.1 | 14.4 | 1,650 | 806 | 7.9 |

[a] Results are averages for the runs listed.

## TABLE 2-19. CDD/CDF DATA FOR QUEBEC CITY

| Test Condition | Run Number | ESP Inlet Temperature (°F)[a] | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Low feed rate, good combustion; ESP = Normal | 2 | 410 | 333 |
| | 10 | 434 | 129 |
| | 11 | 434 | 112 |
| Average | | 426 | 191 |
| Combustor = Design feed rate, good combustion; ESP = Normal | 5 | 423 | 66 |
| | 6 | 434 | 46 |
| | 12 | 457 | 81 |
| Average | | 438 | 64 |
| Combustor = High feed rate, good combustion; ESP = Normal | 7 | 448 | 155 |
| | 9 | 471 | 193 |
| | 13 | 484 | 300 |
| Average | | 468 | 216 |
| Combustor = Design feed rate, low comb. temp.; ESP = Normal | 3 | 464 | 690 |
| | 4 | 470 | 630 |
| Average | | 467 | 660 |
| Combustor = Design feed rate, poor air dist.; ESP = Normal | 14 | 470 | 563 |
| | 15 | 462 | 537 |
| Average | | 464 | 550 |

[a] Estimated from temperature measured at ESP outlet and assumed temperature drop across the ESP (20°F).

At the design feed rate and good combustion conditions (Runs 5, 6, and 12), outlet CDD/CDF concentrations ranged from 46 to 81 ng/dscm and averaged 64 ng/dscm. Under the off-specification combustor conditions (low and high feed rate, low combustion temperature, and poor air distribution), the measured outlet CDD/CDF concentrations were substantially higher, ranging from 112 to 690 ng/dscm. Although it cannot be ascertained because no inlet CDD/CDF data were collected, these higher outlet CDD/CDF results are likely a result of combustor (causing higher ESP inlet values) and ESP performance both.

2.2.1.10 Tulsa.[20] The Walter B. Hall Resource Recovery Facility in Tulsa, Oklahoma, consists of two identical 375-ton/day Martin GmbH mass burn, waterwall combustors. Emissions are controlled by 3-field ESP's with SCA's of 325 $ft^2$/1,000 acfm and design PM removal efficiencies of 98.5 percent. At the ESP inlet, the design flue gas flow is 89,500 acfm at a temperature of 515°F. The ESP normally operates between 375 and 505°F. The ESP exhaust streams exit through a common stack.

In June 1986, compliance testing was performed with the combustor and ESP under normal operating conditions. At each ESP outlet, three separate runs were conducted to measure PM, $NO_x$, $SO_2$, and HCl. At the common stack, three measurements were taken of CDD/CDF, volatile organics, and metals (lead, beryllium, and mercury).

Particulate data from the outlet of both ESP's are presented in Table 2-20. Outlet PM concentrations from Unit 1 ranged from 0.0069 to 0.012 gr/dscf at 12 percent $CO_2$ and averaged 0.0094 gr/dscf. The outlet PM concentrations from Unit 2 ranged from 0.0036 to 0.0056 gr/dscf and averaged 0.0049 gr/dscf.

Table 2-21 presents lead and mercury emissions data from the common stack. Lead and mercury averaged 412 and 418 ug/dscm, respectively. Again, when compared to typical uncontrolled levels measured at other facilities (see Section 1.2), it appears that the ESP's achieved a relatively high level of lead control (99 percent removal efficiency), but little or no mercury control.

The results of three CDD/CDF sample runs conducted at the common stack are presented in Table 2-22. CDD/CDF concentrations ranged from 34 to

TABLE 2-20. PARTICULATE DATA FOR TULSA

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm)[b] | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1-1 | NM | 69,500 | 0.012 |
| ESP = Normal | 1-2 | NM | 77,800 | 0.0093 |
| | 1-3 | NM | 81,000 | 0.0069 |
| Average (Unit 1) | | 375[c] | 76,000 | 0.0094 |
| | 2-1 | NM | 77,600 | 0.0054 |
| | 2-2 | NM | 80,800 | 0.0056 |
| | 2-3 | NM | 81,400 | 0.0036 |
| Average (Unit 2) | | 375[c] | 79,900 | 0.0049 |

[a] The unit number is given first followed by the run number.

[b] Flue gas flow rate (acfm) calculated based on reported dscfm, average moisture value of 17.6 percent, and estimated temperature at the ESP inlet of 375°F. Flue gas flow in acfm is equal to the flow in dscfm times 1.92.

[c] Temperature not measured, but estimated based on a measured value at the stack during the same test program and an assumed temperature drop across the ESP (20°F).

## TABLE 2-21. METALS EMISSIONS DATA FOR TULSA

| Test Condition | Run Number | ESP Inlet Temperature (°F)[a] | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) | |
|---|---|---|---|---|---|
| | | | | Pb | Hg |
| Combustor = Normal | 1 | 362 | -- | 420 | 412 |
| ESP = Normal | 2 | 383 | -- | 490 | 454 |
| | 3 | 379 | -- | 326 | 389 |
| Average | | 375 | 0.0023[b] | 412 | 418 |

[a] Temperature estimated from a measured value at the ESP outlet and an assumed temperature drop across the ESP (20°F).

[b] Particulate samples not collected simultaneously with metal samples. Average particulate results given.

### TABLE 2-22. CDD/CDF DATA FOR TULSA

| Test Condition | Run Number | ESP Inlet Temperature (°F)[a] | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1 | 375 | 35.8 |
| ESP = Normal | 2 | 375 | 33.7 |
|  | 3 | 375 | 38.5 |
| Average |  | 375 | 36.0 |

[a] Temperature estimated based on a measured value at the stack during the metals runs and an assumed temperature drop across the ESP (20°F).

39 ng/dscm at 7 percent $O_2$ and averaged 36 ng/dscm. No inlet CDD/CDF data were collected. The estimated ESP inlet temperature of 375°F is substantially below the temperature range suspected for CDD/CDF formation. This low temperature and correspondingly low CDD/CDF emission level suggest that a well designed and operated ESP coupled with a well designed and operated combustor can achieve relatively low CDD/CDF emission levels.

### 2.2.2 RDF MWC's

2.2.2.1 Lawrence.[21,22] The Lawrence, Massachusetts, Thermal Conversion Facility consists of a single unit designed to combust 1,000 tons/day of RDF. Emissions are controlled using a Belco wire and plate hot-side ESP with 3 fields. The SCA of the ESP is unavailable. At the ESP inlet, the flue gas flow is typically 190,000 acfm at about 540°F. Following the ESP is an air preheater, an ID fan, and the stack.

Test data are available from September 1986 and September 1987. In September 1986, flue gas at the ESP outlet (following the air preheater) was sampled to determine the CDD/CDF emissions from the facility. In September 1987, testing was performed to demonstrate compliance with State permit requirements. At the ESP outlet (downstream of the air preheater), CDD/CDF, $NO_x$, and PM were measured. All tests were conducted under normal combustor and ESP operating conditions.

Particulate emissions data from the September 1987 tests are presented in Table 2-23. The measured particulate emissions from the three test runs ranged from 0.0054 to 0.014 gr/dscf at 12 percent $CO_2$ and averaged 0.010 gr/dscf. No inlet PM or SCA data are available.

In Table 2-24, CDD/CDF data are presented from both the 1986 and 1987 tests. The 1986 tests (3,300 ng/dscm) show approximately 30 times greater CDD/CDF concentration as the 1987 tests (111 ng/dscm). Although modifications were made to the combustor and ESP between the two test periods, the details of the modifications are unavailable. Neither inlet PM nor inlet CDD/CDF were measured.

2.2.2.2 Niagara Falls.[23,24,25] The RDF facility located in Niagara Falls, New York, is operated by the Occidental Chemical Corporation. Each of the two combustors are designed to combust 1,200 tons/day of RDF. Emissions are controlled by Belco 4-field, wire-plate ESP's, each with a design SCA of

TABLE 2-23. PARTICULATE DATA FOR LAWRENCE

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1 | NM[a] | 166,000 | 0.014 |
| ESP = Normal | 2 | NM | 166,600 | 0.011 |
|  | 3 | NM | 160,300 | 0.0054 |
| Average |  | NM | 164,300 | 0.010 |

[a] NM = Not measured. Assuming the same temperature drop across the ESP and air preheater as measured in 1986, the temperature at the ESP inlet would be 507°F. However, because of the modifications made to the system this cannot be verified.

## TABLE 2-24. CDD/CDF DATA FOR LAWRENCE

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1 | 538 | 2,320 |
| ESP = Normal | 2 | 545 | 2,780 |
| (1986) | 3 | 544 | 4,810 |
| Average (1986) | | 542 | 3,300 |
| Combustor = Normal | 1 | NM[a] | 115 |
| ESP = Normal | 2 | NM | 159 |
| (1987) | 3 | NM | 78 |
| | 4 | NM | 90 |
| Average (1987) | | NM | 111 |

[a] NM = Not measured. Assuming the same temperature drop across the ESP and air preheater as measured in 1986, the temperature at the ESP inlet would be 508°F. However, because of the modifications made to the system, this cannot be verified.

520 $ft^2$/1,000 acfm. At the ESP inlet, the design flue gas flow is 280,000 acfm at 550°F. The facility was built in 1981; modifications to the ESP's were made in 1986. These modifications included reduction of air inleakage, improving gas distribution, and improving the rapping system.

In May and June 1985, testing was conducted as part of the New York Department of Environmental Conservation's assessment of risk from municipal waste combustion. The sampling was conducted at Unit 1 of the facility under normal operating conditions. Flue gas at the ESP outlet was sampled and analyzed for CDD/CDF, PM, HCl, $SO_2$, $NO_x$, metals (lead, manganese, mercury, zinc, beryllium, chromium, cadmium, nickel, and vanadium), and other organics. However, because these results reflect operation of the ESP prior to modifications, the PM and CDD/CDF data are presented only for comparison to later results. Because metals data are available from later testing, the metals results from these tests are not included.

Throughout 1986, PM testing was performed in conjunction with modification of the ESP's in order to assess improvements in performance. The combustor steam load was varied during these tests to evaluate the range of inlet conditions typically encountered. In February, prior to modification of the ESP's, PM was measured at the ESP inlet. Following completion of modifications, PM testing at the ESP outlet was conducted in May and August.

In April 1987, testing at the Unit 1 ESP outlet for CDD/CDF only was conducted to assess CDD/CDF emissions. The combustor and ESP were operating normally during this testing.

Particulate data from the 1985 and 1986 tests are presented in Table 2-25. The modifications to the ESP produced significant reductions in PM emissions. Outlet measurements conducted on Unit 1 in 1985 prior to modifications averaged nearly 0.1 gr/dscf at 12 percent $CO_2$. In 1986, outlet emissions ranged from 0.010 to 0.025 gr/dscf and averaged 0.016 gr/dscf for Unit 1 and ranged from 0.023 to 0.028 gr/dscf and averaged 0.025 gr/dscf for Unit 2.

Table 2-26 presents CDD/CDF emissions data. CDD/CDF emission measurements were conducted at the ESP outlet of Unit 1 both before (1985) and after (1987) modifications made to the ESP. Emissions measured during test periods were relatively high (>2000 ng/dscm) and are similar suggesting that the ESP modifications had little effect on CDD/CDF emissions.

## TABLE 2-25. PARTICULATE DATA FOR NIAGARA FALLS

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$)[a,b] | Outlet PM Concentration (gr/dscf at 12% $CO_2$)[a] | PM Removal Efficiency (%)[a] |
|---|---|---|---|---|---|---|
| Before Modifications (1985) | 1-1 | NM[c] | NM | NM | 0.118 | - |
| Combustor = Normal | 1-2 | NM | NM | NM | 0.073 | - |
| ESP = Normal | 1-3 | NM | NM | NM | 0.096 | - |
| Average before modifications | | - | - | - | 0.096 | - |
| After Modifications (1986) | 1-1 | 627 | 273,000 | 3.87 | 0.018[d] | - |
| Combustor = Normal | 1-2 | 627 | 285,000 | 3.42 | 0.015[d] | - |
| ESP = Normal | 1-3 | 628 | 285,000 | 3.18 | 0.014[d] | - |
| | 1-4 | 642 | 291,000 | 2.51 | 0.018[d] | - |
| | 1-5 | 600[e] | 302,000[e] | 2.48 | 0.025 | - |
| | 1-6 | 600[e] | 302,000[e] | 4.03 | 0.020 | - |
| | 1-7 | 600[e] | 302,000[e] | 3.91 | 0.019 | - |
| | 1-8 | 600[e] | 302,000[e] | 4.24 | 0.019 | - |
| | 1-9 | 603[f] | 282,000[f] | 3.91 | 0.011 | - |
| | 1-10 | 603[f] | 282,000[f] | NM | 0.015 | - |
| | 1-11 | 620[g] | 286,000[g] | NM | 0.011 | - |
| | 1-12 | 620[g] | 286,000[g] | NM | 0.010 | - |
| Average (Unit 1) | | 614 | 290,000 | 3.51 | 0.016 | 99.5[h] |
| | 2-1 | 602 | 281,000 | 2.90 | 0.023[d] | - |
| | 2-2 | 618 | 287,000 | 2.65 | 0.024[d] | - |
| | 2-3 | 606 | 280,000 | NM | 0.023[d] | - |
| | 2-4 | 606 | 275,000 | NM | 0.028[d] | - |
| Average (Unit 2) | | 610 | 281,000 | 2.78 | 0.025 | 99.1[h] |

[a] Inlet and outlet PM measurements not taken simultaneously. Cannot calculate removal efficiency per run.

[b] All inlet data collected in February 1986.

[c] NM = Not measured.

[d] August 1986 tests. Other data taken after ESP modifications were collected in May 1986.

[e] Average of four tests at target steam flow of 270,000 lb/hr (90 percent of design).

[f] Average of two tests at target steam flow of 250,000 lb/hr steam (83 percent of design).

[g] Average of two tests at target steam flow of 230,000 lb/hr stream (77 percent of design).

[h] Removal efficiency calculated from average inlet and outlet values for post-modifications tests.

## TABLE 2-26. CDD/CDF DATA FOR NIAGARA FALLS

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1 | NR[a] | 3,140 |
| ESP = Normal, prior | 2 | NR | 2,380 |
| to modification (1985) | 3 | NR | 2,200 |
| Average, prior to modification | | NR | 2,560 |
| Combustor = Normal | 3 | NR | 3,770 |
| ESP = Normal, after | 4 | NR | 5,390 |
| modification (1987) | 5 | NR | 3,700 |
| Average, after modification | | 613[b] | 4,290 |

[a] NR = not reported.

[b] Temperature assumed same as measured for PM tests following ESP modifications.

2.2.2.3 Red Wing (Northern States Power).[26,27] The Northern States Power (NSP) Company Red Wing, Minnesota facility consists of two Foster Wheeler RDF spreader stoker combustors with Detroit Stoker grates capable of firing 360 tons/day of coarse RDF each. In 1987, the two combustors were converted by Babcock & Wilcox from firing coal to firing RDF. Emissions from each combustor are controlled by a cyclone and Belco 4-field wire and plate ESP that were installed in 1981. Each ESP is equipped with 47,250 $ft^2$ of plate surface area and is operated at an SCA of about 570 $ft^2$/1,000 acfm, based on a measured flue gas flow rate of 83,000 acfm at the ESP inlet. The temperature at the ESP inlet is designed to be between 260 and 450$^0$F.

Compliance tests were conducted at the facility on two separate occasions. The first compliance test was conducted in March 1988 on Unit 2. Measurements were made at the ESP inlet and outlet under high load combustor conditions (106,000 to 114,600 lb/hr steam) for PM, metals, CDD/CDF, and other organics. Acid gases and $NO_x$ were also measured at the ESP outlet. However, the CDD/CDF samples obtained at the ESP inlet had analytical problems and have been invalidated.

The second compliance test was conducted in May 1988 on Unit 1 under high load combustor conditions (105,700 to 113,700 lb/hr steam) and on Unit 2 under low load combustor conditions (60,400 to 62,400 lb/hr steam). At Unit 1, PM measurements were made at the ESP outlet. At Unit 2, metals and CDD/CDF measurements were made at the ESP outlet. No inlet samples were collected on either unit.

Particulate data from both test periods are presented in Table 2-27. Outlet PM emissions from three runs ar Unit 2 under high load conditions ranged from 0.015 to 0.046 gr/dscf at 12 percent $CO_2$ and averaged 0.024 gr/dscf. The corresponding removal efficiencies ranged from 98.3 to 99.3 percent and averaged 98.9 percent. Outlet PM emissions from four runs at Unit 1, under similar high load conditions, ranged from 0.031 to 0.055 gr/dscf at 12 percent $CO_2$ and averaged 0.041 gr/dscf. There is insufficient information available to determine why the emissions from Unit 1 were generally higher than from Unit 2. The highest outlet PM concentrations from both units resulted when sootblows occurred. This generated a 40 to 80

## TABLE 2-27. PARTICULATE DATA FOR NSP RED WING

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F) | Flue Gas Flow[b] (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = High Load | 2-1 | 416 | 83,900 | 1.50 | 0.011 | 99.3 |
| ESP = Normal | 2-2 | 417 | 82,700 | 2.71[c] | 0.046[c] | 98.3 |
|  | 2-3 | 407 | 82,300 | 1.95 | 0.015 | 99.2 |
| Average |  | 413 | 83,000 | 2.05 | 0.024 | 98.9 |
| Combustor = High Load | 1-1 | 454[d] | 90,600 | NM[e] | 0.18[f,g] | -- |
| ESP = Normal | 1-2 | 457[d] | 90,900 | NM | 0.055[c,g] | -- |
|  | 1-3 | 464[d] | 89,600 | NM | 0.036[g] | -- |
|  | 1-4 | 458[d] | 100,800 | NM | 0.031[g] | -- |
| Average |  | 458 | 92,900 | NM | 0.041 | -- |

[a] Run Number contains the unit number followed by the run number for each unit.

[b] Flue gas flow rate measurement believed to be high due to turbulence at sampling location.

[c] Includes sootblow.

[d] Temperature estimated from measured value at the stack and a previously measured temperature drop across the ESP (50°F).

[e] NM = not measured.

[f] Considered erroneous by testing company. Not included in average.

[g] Includes condensible fraction that cannot be separately quantified based on test report data. This fraction was previously measured at Unit 2 to be 5.4 to 16.8 percent of the total particulate sample.

percent higher inlet PM loading, as shown by Unit 2, which in turn increased the outlet PM concentration. The PM removal efficiency also decreased during the sootblow.

Metals data from three runs each at low and high load conditions on Unit 2 are presented in Table 2-28. During high load operation, cadmium and lead were consistently removed at greater than 99 percent efficiency, similar to the PM removal efficiency. Removal efficiencies for arsenic, chromium, mercury, and nickel were lower. Arsenic removal efficiencies ranged from 78.0 to 99.3 percent and averaged 90.9 percent. Mercury removal efficiency ranged from 74.8 to 86.0 percent and averaged 81.6 percent. This is highly unusual since mercury removal has not been observed across any other ESP. In the test report, it is suggested that mercury is removed because it is in the form of salts. However, other ESP's operating at similar conditions have not demonstrated mercury reductions. Chromium removal efficiencies ranged from 67.3 to 97.5 percent and averaged 80.7 percent. Nickel removal efficiencies were relatively low, ranging from 41.9 to 82.3 percent and averaging 64.5 percent.

Outlet metals emissions were lower at low load than at high load for all metals except mercury. There are no data on ESP operation to suggest a reason for the generally better performance at low load. The lower metals emissions may be due to lower PM emissions because the combustor generates less PM at low load conditions or due to a lower flue gas flow resulting in a higher SCA, which provides better PM removal.

CDD/CDF data are presented in Table 2-29 for six outlet sample runs on Unit 2. Three runs were conducted under high load conditions and three runs were conducted under low load conditions. At high load, outlet CDD/CDF concentrations ranged from 26.5 to 34.1 ng/dscm at 7 percent $O_2$ and averaged 29.3 ng/dscm. Concentrations obtained during low load were similar, ranging from 22.0 to 48.7 ng/dscm at 7 percent $O_2$ and averaging 32.7 ng/dscm. Although the ESP inlet temperature during low load was about 45°F less than at high load, the CDD/CDF emissions were not significantly different.

## TABLE 2-28. METALS DATA FOR NSP RED WING

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Inlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Removal Efficiency (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = High Load<br>ESP = Normal | 2-1 | NM[b] | NM | 109 | 777 | 459 | 28,910 | 131 | 408 | 24 | 5.6 | 150 | 77 | 33 | 237 | 78.0 | 99.3 | 67.3 | 99.7 | 74.8 | 41.9 |
| | 2-2 | NM | NM | 326 | 935 | 286 | 17,350 | 114 | 296 | 15 | 2.7 | 65 | 39 | 16 | 91 | 95.4 | 99.7 | 77.3 | 99.8 | 86.0 | 69.3 |
| | 2-3 | NM | NM | 173 | 702 | 399 | 26,580 | 176 | 327 | 1.2 | 0.1 | 10 | 27 | 28 | 58 | 99.3 | 99.9 | 97.5 | 99.9 | 84.1 | 82.3 |
| Average | | 413[c] | 0.024[d] | 203 | 805 | 381 | 24,280 | 140 | 344 | 13 | 2.8 | 75 | 48 | 26 | 129 | 90.9 | 99.7 | 80.7 | 99.8 | 81.6 | 64.5 |
| Combustor = Low Load<br>ESP = Normal | 2-1 | NM | NM | NM | NM | NM | NM | NM | NM | 5.2 | 1.0 | 24 | 5.3 | 61 | 40 | - | - | - | - | - | - |
| | 2-2 | NM | NM | NM | NM | NM | NM | NM | NM | 1.4 | 1.1 | 21 | 3.8 | 15 | 26 | - | - | - | - | - | - |
| | 2-3 | NM | NM | NM | NM | NM | NM | NM | NM | 3.4 | 0.9 | 16 | 13 | 111 | 37 | - | - | - | - | - | - |
| Average | | 390[c] | NM | NM | NM | NM | NM | NM | NM | 3.3 | 1.0 | 20 | 7.4 | 62 | 34 | - | - | - | - | - | - |

[a] Run Number contains the unit number followed by the run number for each unit.

[b] NM = not measured.

[c] Average temperature for other tests at the same condition.

[d] PM not measured simultaneously. Average for Unit 2 reported.

TABLE 2-29. CDD/CDF DATA FOR NSP RED WING

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = High Load | 2-1 | 421 | 26.5 |
| ESP Normal | 2-2 | 424 | 27.4 |
| | 2-3 | 431 | 34.1 |
| Average | | 425 | 29.3 |
| Combustor = Low Load | 2-1 | 378[b] | 22.0 |
| ESP = Normal | 2-2 | 388[b] | 27.5 |
| | 2-3 | 389[b] | 48.7 |
| Average | | 380 | 32.7 |

[a] Run number contains the unit number followed by the run number for that unit.

[b] Temperature estimated from measured value at the stack and a previously measured temperature drop across the ESP (50°F).

### 2.2.3 Modular MWC's

2.2.3.1 Barron County.[28] The Barron County Resource Recovery Facility in Almena, Wisconsin, consists of two Consumat Model Number CS-1600 starved-air combustors. Each combustor has a rated capacity of 50 tons/day. Emissions are controlled by wire-plate 2-field ESP's, manufactured by Precipitair Pollution Control. Each ESP has an SCA of 230 $ft^2$/1,000 acfm. The design flue gas flow at the ESP inlet is 12,500 acfm at 525°F.

In November 1986, compliance tests were conducted at the facility under normal combustor and ESP operating conditions. Flue gas was sampled during three runs at the ESP outlet for PM, HCl, $NO_x$, and trace metals (lead, arsenic, cadmium, chromium, and nickel).

Particulate data from the testing at Barron County are presented in Table 2-30. The outlet PM concentration ranged from 0.010 to 0.011 and averaged 0.010 gr/dscf at 12 percent $CO_2$. No inlet PM data were collected.

The metals emissions data from Barron County are presented in Table 2-31. Lead, cadmium, arsenic and chromium concentrations at the ESP outlet averaged 270, 22, 21, and 2.9 ug/dscm at 7 percent $O_2$, respectively. Nickel was not detected. Compared to typical uncontrolled metals concentrations from starved-air modular MWC's (Section 1.2), removal efficiencies for cadmium, chromium, nickel, and lead probably exceeded 98 percent. Arsenic removal efficiency appears to be somewhat lower, perhaps 60 percent.

2.2.3.2 Oneida County.[29,30] The Oneida County Energy Recovery Facility in Rome, New York, combusts MSW in four Clear Air Model Number CA 4000A starved-air modular combustors. Each is designed to combust 50 tons/day MSW. United-McGill ESP's, each with 2 fields and a design SCA of 232 $ft^2$/1,000 acfm, control emissions from each combustor. At the ESP inlet, the design flue gas flow is 18,000 acfm at 400°F. The design PM removal efficiency is 90 percent. Controlled emissions are released through independent stacks for each unit.

Testing was conducted at the facility in August 1985 as part of the New York State Department of Environmental Conservation's MWC test program. Emission tests were conducted at the outlet of Unit 1 for PM, CDD/CDF, other organics (chrysene, PCB's, benzo(a)pyrene, formaldehyde), HCl, HF, various

TABLE 2-30. PARTICULATE DATA FOR BARRON COUNTY

| Test Condition | Run Number | ESP Inlet Temperature (°F)[a] | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1 | 437 | 23,900 | 0.011 |
| ESP = Normal | 2 | 444 | 24,600 | 0.010 |
| | 3 | 448 | 25,200 | 0.010 |
| Average | | 443 | 24,600 | 0.010 |

[a] Temperature estimated from measured value at ESP outlet and an assumed temperature drop across the ESP (40°F).

## TABLE 2-31. METALS EMISSIONS DATA FOR BARRON COUNTY

| Test Condition | Run Number | ESP Inlet Temperature (°F)[a] | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Ni |
| Combustor = Normal | 1 | 437 | 0.011 | 19 | 19 | ND[b] | 235 | ND |
| ESP = Normal | 2 | 444 | 0.010 | 22 | 24 | 4.3 | 287 | ND |
| | 3 | 448 | 0.010 | 22 | 24 | 4.4 | 287 | ND |
| Average | | 443 | 0.010 | 21 | 22 | 2.9 | 270 | ND |

[a] Temperature estimated from a measured value at the ESP outlet and an assumed temperature drop across the ESP (40°F).

[b] ND = not detected. Considered zero for evaluating averages.

metals (arsenic, beryllium, mercury, cadmium, chromium, lead, manganese, nickel, vanadium, and zinc), $SO_2$, and $NO_x$. Both the combustor and ESP were operated normally during testing. However, temperature data were not reported for any location.

Particulate data from the three sample runs conducted are presented in Table 2-32 The outlet PM concentration ranged from 0.013 to 0.033 gr/dscf and averaged 0.026 gr/dscf at 12 percent $CO_2$. No inlet PM data are available.

The metals data from Oneida County are presented in Table 2-33. Outlet metals concentrations averaged 5.0, 92, 150, 430, 2,100, and 130 ug/dscm for arsenic, cadmium, chromium, lead, mercury, and nickel, respectively. Based on typical uncontrolled metals concentration (Section 1.2), removal of arsenic, cadmium, and nickel was moderate, about 90 percent. Lead removal was somewhat higher (about 98 percent), while chromium removal was soemwhat lower (about 70 percent). The outlet mercury levels suggested that no removal of mercury was achieved.

Table 2-34 presents CDD/CDF data for the two outlet sample runs conducted. The CDD/CDF concentrations measured were 327 and 597 ng/dscm at 7 percent $O_2$, for an average of 462 ng/dscm.

2.2.3.3 Oswego County.[31] The Oswego County Energy Recovery Facility in Fulton, New York, includes four identical 50 tons/day starved-air combustors manufactured by Consumat. Each combustor is equipped with a 1-field ESP manufactured by PPC Incorporated. Each ESP is designed to treat 15,250 acfm of flue gas at 450°F. The design SCA is 294 $ft^2$/1,000 acfm and the design PM removal efficiency is 80 percent. The actual SCA is between 220 and 250 $ft^2$/1,000 acfm. Cleaned flue gas from each incinerator is exhausted through a separate stack.

In August 1986, a test program was conducted at the facility to determine operating characteristics which minimize formation of CDD/CDF and assess performance of the air pollution control device. Specifically, relationships between combustion gas variables and CDD/CDF were analyzed. Twelve test runs were conducted during the test program, with triplicate runs at four test conditions: (1) start of campaign (normal operation, cleaned heat transfer surfaces); (2) mid-range secondary chamber temperature

TABLE 2-32. PARTICULATE DATA FOR ONEIDA COUNTY

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1 | NM[a] | NA[b] | 0.013 |
| ESP = Normal | 2 | NM | NA | 0.033 |
| | 3 | NM | NA | 0.033 |
| Average | | NM | NA | 0.026 |

[a] NM = Not measured.

[b] NA = Not available. Flue gas flow not present in test report.

TABLE 2-33. METALS EMISSIONS DATA FOR ONEIDA COUNTY

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal<br>ESP = Normal | 1 | NM[a] | 0.013 | 5.09 | 89.2 | 16 | 636 | 3,200 | 44 |
| | 2 | NM | 0.033 | 6.09 | 78.6 | 274 | 308 | 1,690 | 222 |
| | 3 | NM | 0.033 | 3.91 | 107 | 159 | 352 | 1,290 | 110 |
| Average | | NM | 0.026 | 5.03 | 91.6 | 150 | 432 | 2,060 | 125 |

[a] NM = Not measured.

## TABLE 2-34. CDD/CDF DATA FOR ONEIDA COUNTY

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1 | NM[a] | 597 |
| ESP = Normal | 2 | NM | 327 |
| Average | | NM | 462 |

[a] NM = Not measured.

(1,750°F); (3) end of campaign (normal operation, dirty heat transfer surfaces); and (4) low secondary chamber temperature (1,650°F). Flue gas was sampled simultaneously at the secondary chamber exit, ESP inlet, and ESP outlet for CDD/CDF, other organics, and HCl. PM was also measured simultaneously at the ESP inlet and outlet. Combustion gases (including CO, $CO_2$, $O_2$, $NO_x$, and $SO_2$) were measured at the secondary chamber exit and ESP outlet.

Results of the particulate tests conducted at Oswego County are presented in Table 2-35. The outlet PM concentration ranged from 0.011 to 0.042 and averaged 0.020 gr/dscf at 7 percent $O_2$ (approximately equal to 0.019 gr/dscf at 12 percent $CO_2$). The PM removal efficiency averaged 92 percent, which is significantly higher than the design value. Variations in flue gas flow rate, and thus, in SCA were too narrow to examine any effect of SCA on PM removal efficiency. Figure 2-10 presents a plot of PM removal efficiency versus inlet PM concentration. PM removal efficiency increased with inlet PM concentration for each test condition except during the tests with low secondary combustion chamber outlet temperature. Figure 2-11 presents a plot of outlet PM concentration as a function of inlet PM concentration. The data from the individual test conditions do not show any causal relationship.

Table 2-36 presents the results of the CDD/CDF test runs conducted at Oswego County. An increase in CDD/CDF concentration across the ESP was observed during all runs except one. The ESP inlet temperature, which ranged from 460 to 500°F, was within the temperature region suggested for CDD/CDF formation (Section 2.1). In Figure 2-12, CDD/CDF removal efficiency is shown as a function of ESP inlet temperature. Formation of CDD/CDF was lower (removal efficiency less negative) at temperatures below 475°F. Figure 2-13 presents a plot of CDD/CDF removal efficiency as a function of inlet CDD/CDF concentration. As shown, CDD/CDF formation was also lower for runs with higher inlet CDD/CDF concentrations.

2.2.3.4 Pigeon Point.[32] The Energy Generating Facility in Pigeon Point (Wilmington), Delaware, consists of five Vicon excess-air modular combustors. Each combustor has a rated capacity of 120 tons per day of RDF, but

TABLE 2-35. PARTICULATE DATA FOR OSWEGO COUNTY

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration[a] (gr/dscf at 7% $O_2$) | Outlet PM Concentration[a] (gr/dscf at 7% $O_2$) | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal, | 1 | 494 | 19,700 | 0.495 | 0.026 | 94.8 |
| start of campaign | 2 | 493 | 20,400 | 0.331 | 0.020 | 94.0 |
| ESP = Normal | 3 | 502 | 20,100 | 0.203 | 0.028 | 86.2 |
| Average | | 496 | 20,100 | 0.343 | 0.025 | 91.7 |
| Combustor = Mid-range | 4 | 486 | 19,300 | 0.182 | 0.013 | 92.9 |
| temperature (1,750°F) | 5 | 492 | 19,600 | 0.224 | 0.012 | 94.6 |
| ESP = Normal | 6 | 487 | 18,300 | 0.155 | 0.023 | 85.2 |
| Average | | 488 | 19,100 | 0.187 | 0.016 | 90.9 |
| Combustor = Normal, | 7 | 487 | 19,700 | 0.301 | 0.013 | 95.7 |
| end of campaign | 8 | 497 | 19,900 | 0.151 | 0.011 | 92.7 |
| ESP = Normal | 9 | 506 | 19,400 | 0.183 | 0.011 | 94.0 |
| Average | | 497 | 19,700 | 0.212 | 0.012 | 94.1 |
| Combustor = Low temperature | 10 | 460 | 17,700 | 0.264 | 0.019 | 92.8 |
| (1,650°F) | 11 | 472 | 19,100 | 0.398 | 0.042 | 89.5 |
| ESP = Normal | 12 | 477 | 19,000 | 0.372 | 0.024 | 93.6 |
| Average | | 470 | 18,600 | 0.344 | 0.028 | 92.0 |

[a] PM data in gr/dscf at 7 percent $O_2$ because $CO_2$. Values are approximately 6 percent larger than if the concentration were normalized to 12 percent $CO_2$, based on the theoretical relationship between $O_2$ and $CO_2$.

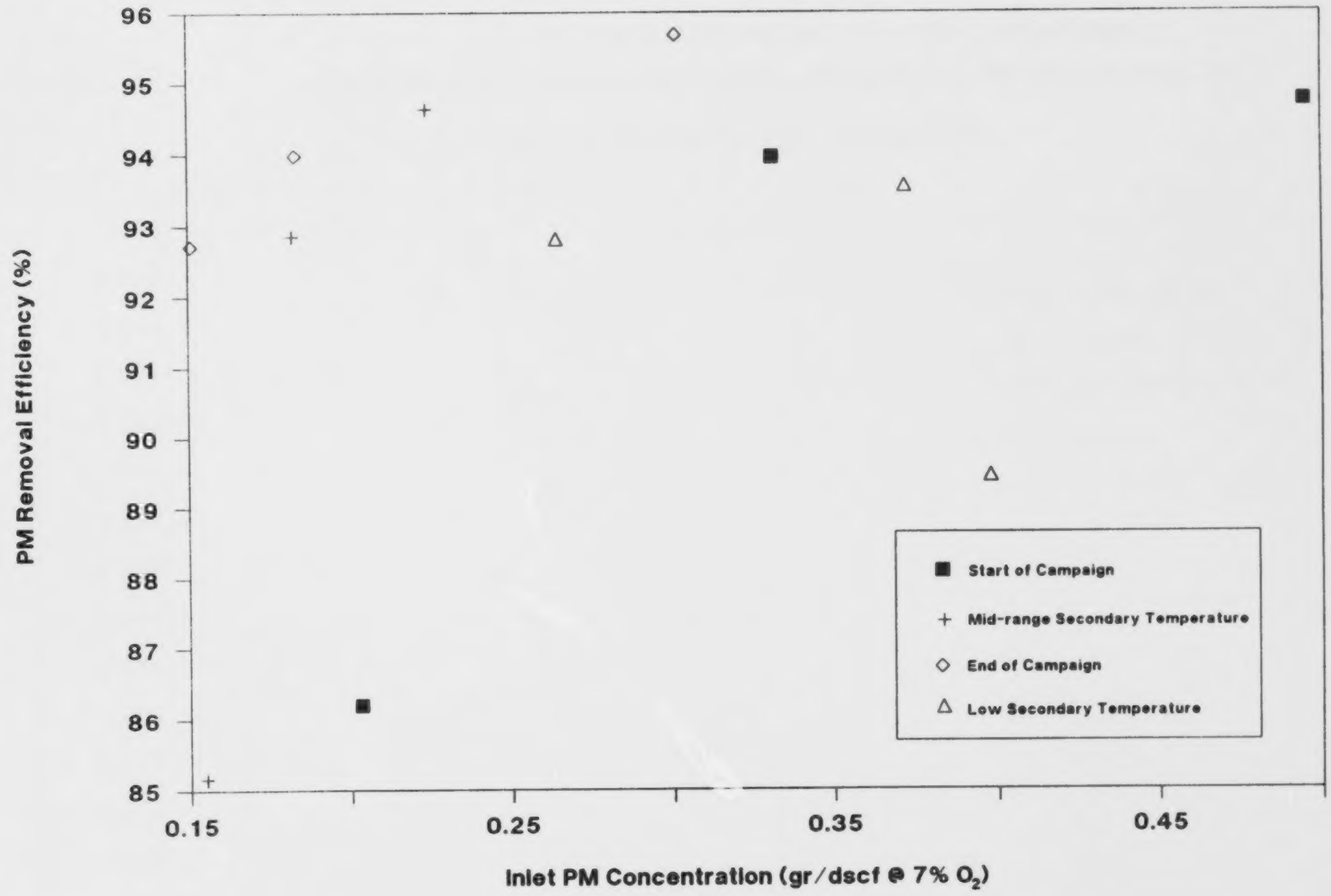


Figure 2-10. PM removal efficiency as a function of inlet PM concentration at the Oswego County MWC.

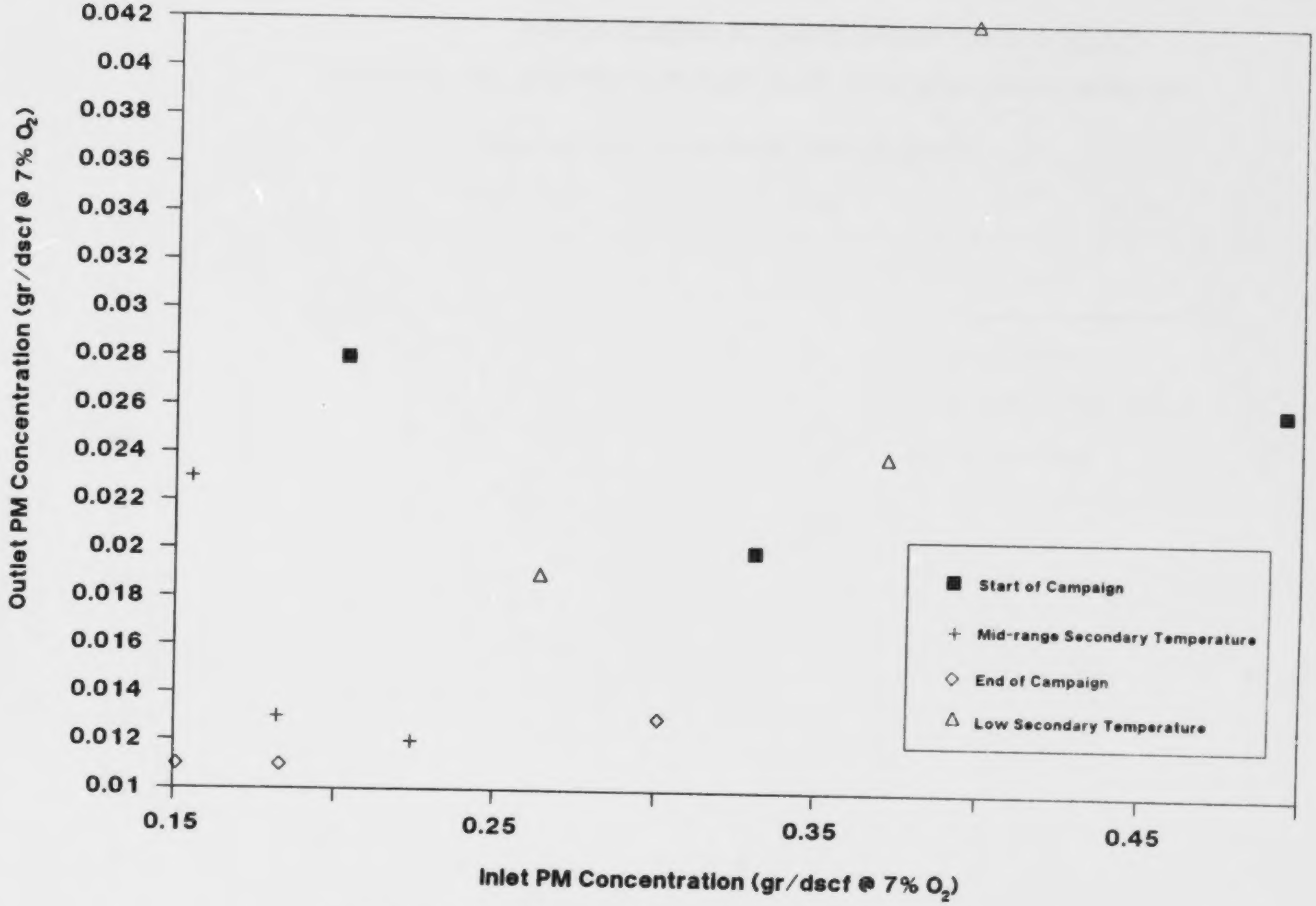


Figure 2-11. Outlet PM concentration as a function of inlet PM concentration at the Oswego County MWC.

## TABLE 2-36. CDD/CDF DATA FOR OSWEGO COUNTY

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (%) |
|---|---|---|---|---|---|
| Combustor = Normal, start of campaign ESP = Normal | 1 | 497 | 205 | 366 | - 78.8 |
|  | 2 | 489 | 208 | 349 | - 67.7 |
|  | 3 | 496 | 112 | 343 | -207 |
| Average |  | 494 | 175 | 353 | -118 |
| Combustor = Mid-range temperature (1,750°F) ESP = Normal | 4 | 483 | 222 | 357 | - 60.4 |
|  | 5 | 485 | 188 | 277 | - 47.3 |
|  | 6 | 481 | 175 | 268 | - 52.5 |
| Average |  | 483 | 195 | 301 | - 53.4 |
| Combustor = Normal, end of campaign ESP = Normal | 7 | 484 | 299 | 377 | - 26.2 |
|  | 8 | 490 | 505 | 280 | 44.5 |
|  | 9 | 500 | 274 | 579 | -111 |
| Average |  | 491 | 359 | 412 | - 30.9 |
| Combustor = Low temperature (1,650°F) ESP = Normal | 10 | 465 | 876 | 965 | - 10.2 |
|  | 11 | 461 | 669 | 818 | - 22.2 |
|  | 12 | 474 | 650 | 674 | - 3.6 |
| Average |  | 467 | 732 | 819 | - 12.0 |

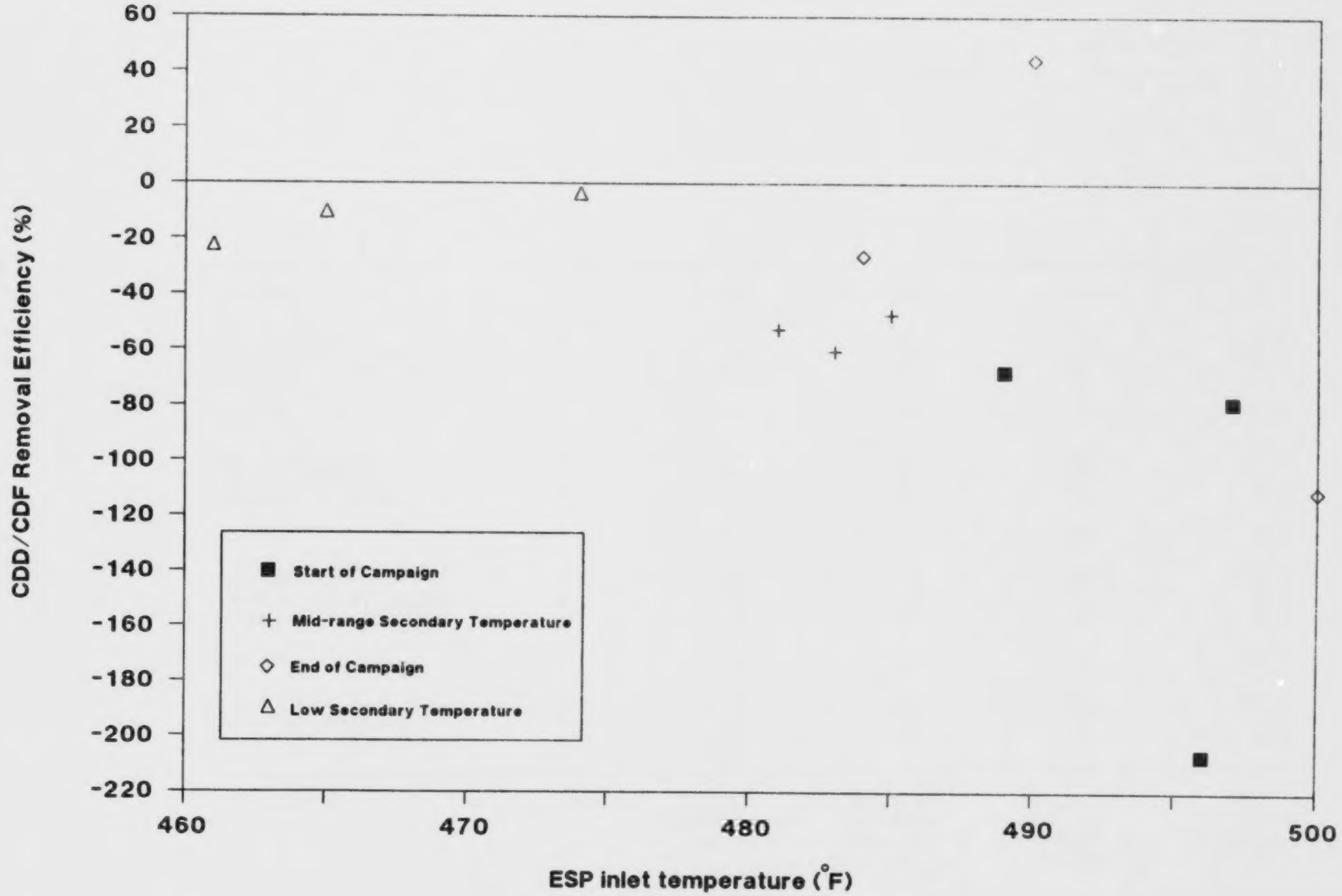


Figure 2-12. CDD/CDF removal efficiency as a function of ESP inlet temperature at the Oswego County MWC.

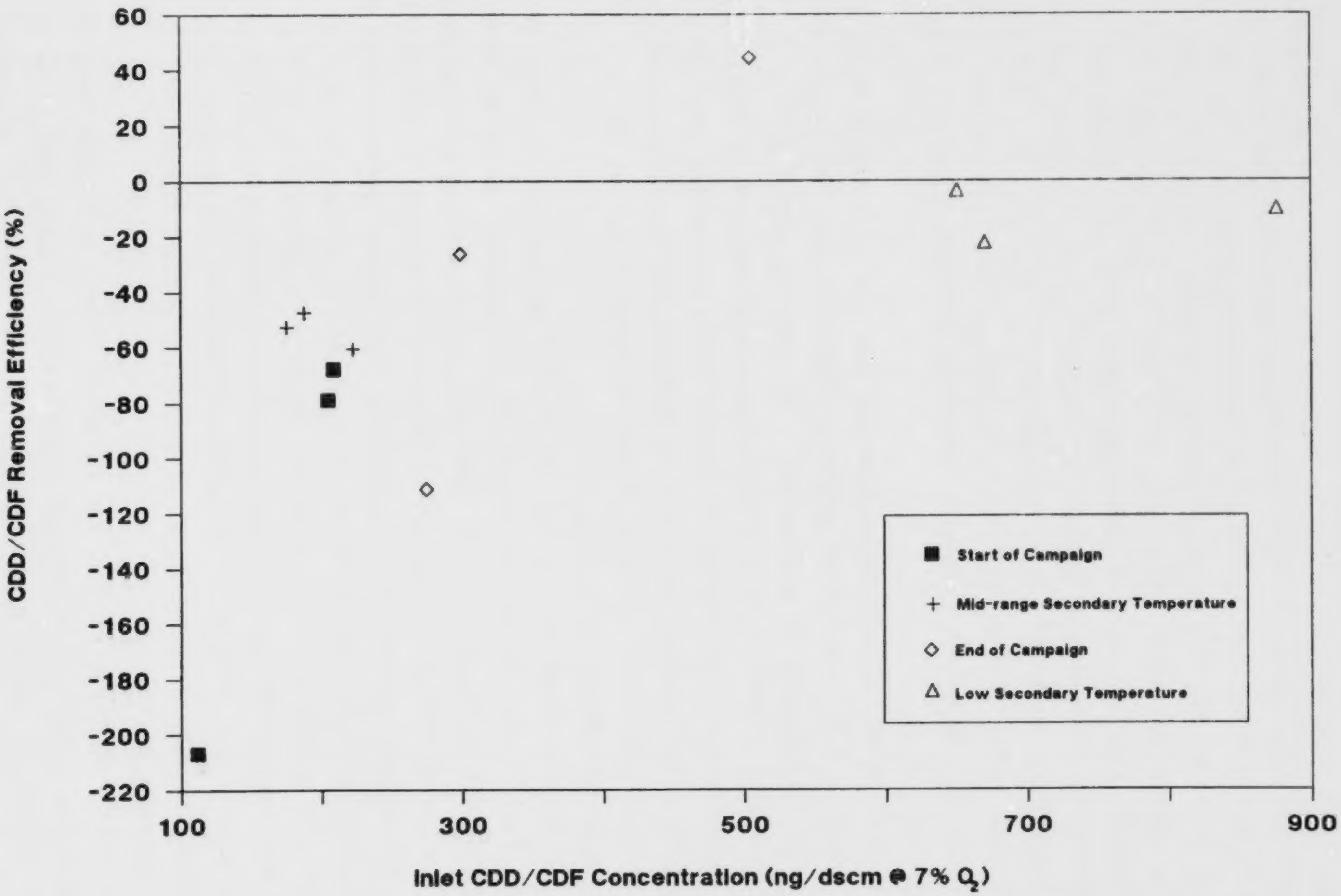


Figure 2-13. CDD/CDF removal efficiency as a function of inlet CDD/CDF concentration at the Oswego County MWC.

unprocessed MSW can also be fired. The RDF ranges in size from 3 to 18 inches. Emissions are controlled by four 3-field ESP's manufactured by Precipitair Pollution Control. Two ESP's control emissions from three combustors and two ESP's control emissions from two combustors. The ESP's have design SCA's of 307 $ft^2$/1,000 acfm at 90,000 acfm flue gas flow and 400°F. The design PM removal efficiency of the ESP's is 97 percent.

In December 1987 and January 1988, compliance tests were conducted. Three simultaneous inlet/outlet measurements were made for PM across all four ESP's. In addition, each ESP outlet was sampled for $SO_2$, $SO_3$, HCl, and $NO_x$ during the same tests. At the outlet of the number 2 ESP flue gas was also tested for CDD/CDF and metals (arsenic, beryllium, chromim, lead, mercury, and nickel).

Results of the particulate tests from all four ESP's at Pigeon Point are presented in Table 2-37. Outlet PM emissions were very low, ranging from 0.0012 to 0.0080 gr/dscf at 12 percent $CO_2$. The average outlet PM concentrations were 0.0029, 0.0015, 0.0019, and 0.0053 gr/dscf at flues 1, 2, 3, and 4, respectively. The average PM removal efficiencies for all four ESP's ranged from 98.7 percent at flue 4 to 99.8 percent for flues 1 and 3. There was no apparent effect of inlet PM concentration on outlet PM concentration or PM removal efficiency.

Metals data from three runs at the outlet of flue 2 at Pigeon Point are presented in Table 2-38. Outlet concentrations for arsenic, chromium, lead, mercury, and nickel averaged 0.83, 24, 150, 360, and 44 ug/dscm at 7 percent $O_2$. Based on typical values for uncontrolled metals emissions for RDF MWC's, (Section 1.2), the ESP appears to have achieved high removal (greater than 98 percent) of lead, arsenic, and chromium. Nickel control appears to be somewhat less, at approximately 90 percent. Mercury concentrations at the ESP outlet were roughly 30 percent lower than typical uncontrolled levels. However, because of the substantial variation in uncontrolled mercury concentrations from RDF-fired MWC's, it is uncertain whether mercury reductions occurred.

CDD/CDF data from three runs at the outlet of flue 2 at Pigeon Point ar presented in Table 2-39. Outlet CDD/CDF concentrations ranged from 71 to 14 ng/dscm at 7 percent $O_2$ and averaged 105 ng/dscm. The ESP inlet temperature

TABLE 2-37. PARTICULATE DATA FOR PIGEON POINT

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal | 1-1 | 434 | 67,300 | 0.695 | 0.0017 | 99.8 |
| ESP = Normal | 1-2 | 430 | 74,600 | 0.940 | 0.0019 | 99.9 |
| | 1-3 | 435 | 70,300 | 1.45 | 0.0052 | 99.6 |
| Average (Flue 1) | | 433 | 70,700 | 1.03 | 0.0029 | 99.8 |
| | 2-1 | 434 | 84,100 | 0.481 | 0.0013 | 99.7 |
| | 2-2 | 422 | 80,100 | 2.07 | 0.0012 | 99.9 |
| | 2-3 | 435 | 88,900 | 0.562 | 0.0021 | 99.6 |
| Average (Flue 2) | | 430 | 84,400 | 1.04 | 0.0015 | 99.7 |
| | 3-1 | 404 | 57,000 | 0.410 | 0.0154[b] | 96.2[b] |
| | 3-2 | 393 | 61,600 | 1.77 | 0.0014 | 99.9 |
| | 3-3 | 381 | 52,200 | 0.513 | 0.0023 | 99.6 |
| Average (Flue 3) | | 393 | 56,900 | 0.898 | 0.0019 | 99.8 |
| | 4-1 | 418 | 64,900 | 0.406 | 0.0080 | 98.0 |
| | 4-2 | 421 | 68,500 | 0.461 | 0.0021 | 99.5 |
| | 4-3 | 402 | 61,600 | 0.429 | 0.0058 | 98.7 |
| Average (Flue 4) | | 414 | 65,000 | 0.432 | 0.0053 | 98.7 |

[a] Run Number contains the flue number followed by the run number for each flue. Flue numbers 1 and 2 are for three incinerators at 120 tpd each. Flue numbers 3 and 4 are for two incinerators at 120 tpd each.

[b] Nozzle on sample train at outlet may have scraped port wall, causing contamination. Outlet concentration and removal efficiency not included in average.

TABLE 2-38. METALS EMISSIONS DATA FOR PIGEON POINT

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F)[b] | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) As | Cr | Pb | Hg | Ni |
|---|---|---|---|---|---|---|---|---|
| Combustor = Normal<br>ESP = Normal | 2-1 | 403 | -- | 0.925 | 45.8 | 190 | 370 | 47.1 |
| | 2-2 | 413 | -- | 0.878 | 8.8 | 127 | 385 | 7.4 |
| | 2-3 | 415 | -- | 0.695 | 16.4 | 146 | 333 | 77.2 |
| Average | | 410 | 0.0030[c] | 0.833 | 23.7 | 154 | 363 | 43.9 |

[a] Run Number contains the flue number followed by the run number for each flue.

[b] Temperature estimated based on measured value at ESP outlet and previously measured temperature drop across the ESP (38°F).

[c] PM samples not collected simultaneously. Average result reported.

## TABLE 2-39. CDD/CDF DATA FOR PIGEON POINT

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F)[b] | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 2-1 | 411 | 102 |
| ESP = Normal | 2-2 | 414 | 70.8 |
| | 2-3 | 411 | 142 |
| Average | | 412 | 105 |

[a] Run Number contains the unit number followed by the run number on that unit.

[b] Temperature estimated based on measured value at ESP outlet and previously measured temperature drop across the ESP (38°F).

remained at about 410°F during all three test runs. Although these CDD/CDF values are relatively low, whether this is due to combustor or ESP performance or both cannot be ascertained because no inlet CDD/CDF measurements were made.

2.2.3.5 Pope/Douglas.[33,34] The Pope/Douglas Waste to Energy Facility in Alexandria, Minnesota, includes two 38 tons/day excess-air modular combustors manufactured by Cadoux, Inc. Emissions are controlled by 2-field plate/plate ESP's made by United McGill. The SCA of each ESP is 466 $ft^2$/1,000 acfm with a design PM removal efficiency of 93 percent. The design flue gas flow at the ESP inlet is 16,900 acfm at 400°F. The controlled emissions exit through a common stack.

A compliance test was conducted in July 1987. All tests were performed under normal combustor and ESP operating conditions. Particulate measurements were made at the outlet of both units. Additional measurements for CDD/CDF, lead, beryllium, arsenic, HCl, $SO_2$, $NO_x$, and other organics were made at the outlet of Unit 2.

Results of the three test runs at each of the two units at Pope/Douglas are presented in Table 2-40. The outlet particulate emissions from Unit 1 ranged from 0.022 to 0.029 gr/dscf at 12 percent $CO_2$ and averaged 0.025 gr/dscf. Emissions from Unit 2 ranged from 0.034 to 0.042 gr/dscf at 12 percent $CO_2$ and averaged 0.037 gr/dscf. The higher PM emissions measured for Unit 2 may have been due to the rapping system in one of the ESP fields having been out of service prior to testing. Although the rapping system was repaired, PM buildup on the collection plate may not have had time to fully clear before the testing.

Metals data from the outlet of Unit 2 are presented in Table 2-41. Outlet concentrations from three runs for arsenic and lead averaged 1.2 and 980 ug/dscm, respectively. The one sample collected for mercury had a concentration of 130 ug/dscm. Based on typical uncontrolled metals concentrations, lead and arsenic were removed relatively effectively (greater than 97 percent). Although mercury emissions are about 90 percent lower than typical uncontrolled values, the wide variability in incontrolled mercury levels and lack of inlet mercury data at Pope/Douglas prevent drawing any conclusions.

## TABLE 2-40. PARTICULATE DATA FOR POPE/DOUGLAS

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F)[b] | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1-1 | 480 | 13,200 | 0.024 |
| ESP = Normal | 1-2 | 483 | 13,800 | 0.029 |
| | 1-3 | 477 | 13,800 | 0.022 |
| Average (Unit 1) | | 484 | 13,600 | 0.025 |
| | 2-1 | 480 | 13,700 | 0.042 |
| | 2-2 | 490 | 13,500 | 0.034 |
| | 2-3 | 482 | 13,400 | 0.034 |
| Average (Unit 2) | | 484 | 13,500 | 0.037 |

[a] Run Number contains the unit number followed by the run number on that unit.

[b] Temperature estimated from measured temperature at the ESP outlet and an assumed temperature drop across the ESP (65°F).

TABLE 2-41. METALS EMISSIONS DATA FOR POPE/DOUGLAS

| Test Condition | Run Number[a] | ESP Inlet Temperature ($^oF$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration ($\mu$g/dscm at 7% $O_2$) | | |
|---|---|---|---|---|---|---|
| | | | | As | Pb | Hg |
| Combustor = Normal<br>ESP = Normal | 2-1 | NM[b] | -- | 1.35 | 773 | 133 |
| | 2-2 | NM | -- | 0.95 | 1,492 | NM |
| | 2-3 | NM | -- | 1.15 | 685 | NM |
| Average | | 482[c] | 0.031[d] | 1.15 | 983 | 133 |

[a] Run Number contains the unit number followed by the run number for each unit.

[b] NM = not measured.

[c] Temperature assumed to be at average value of PM tests.

[d] PM not measured simultaneously with metals. Average PM concentration reported.

Table 2-42 presents CDD/CDF emissions data from three runs at the outlet of Unit 2. CDD/CDF concentrations ranged from 358 to 529 ng/dscm at 7 percent $O_2$ and averaged 416 ng/dscm. No inlet PM or CDD/CDF data are available. The inlet temperature was consistently about 500°F during all three runs.

## 2.3 SUMMARY OF PERFORMANCE

As discussed in the preceding review of available data from individual units, the measured values of key operating variables that affect the performance of an individual ESP generally cover too narrow a range to allow meaningful analysis of their effect on ESP performance. This section examines the combined data from all of the facilities tested to evaluate relationships between key operating parameters and performance. In general, more data are available to characterize performance in terms of outlet emissions rather than removal efficiency due to the absence of simultaneous measurements at ESP inlets at most facilities.

### 2.3.1 Particulate Matter

As discussed in Section 2.1, several measurable parameters can affect PM performance. These include the number of fields, temperature, resistivity, SCA, and inlet PM concentration. Figure 2-14 shows the the available data on PM removal efficiencies and outlet PM concentrations as a function of the number of ESP fields. Most of these data are from compliance test reports and represent averages of multiple runs, typically three. Because data are available for only one 1-field ESP, the plotted data for 1-field ESP's represent 12 runs at Oswego. As is shown, performance generally improves as the number of fields increases, although there are no distinct boundaries between the ranges. All but one of the ESP's tested achieved an average PM concentration of 0.03 gr/dscf or less. Several of the ESP's demonstrated outlet PM emissions of 0.01 gr/dscf or less. Five of nine 2-field ESP's, ten of fifteen 3-field ESP's, and three of seven 4-field ESP's tested achieved average PM concentrations of 0.01 gr/dscf or less. These facilities include three units at Baltimore RESCO, designed to achieve outlet PM concentrations of 0.017 gr/dscf, and Unit 3 at Dayton, designed to achieve 0.015 gr/dscf. Thus, the ESP's achieving outlet PM concentrations of 0.01 gr/dscf are

## TABLE 2-42. CDD/CDF DATA FOR POPE/DOUGLAS

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F)[b] | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 2-1 | 490 | 453 |
| ESP = Normal | 2-2 | 503 | 529 |
| | 2-3 | 495 | 358 |
| Average | | 496 | 446 |

[a] Run Number contains the unit number followed by the run number on that unit.

[b] Temperature estimated from measured temperature at the ESP outlet and an assumed temperature drop across the ESP (65°F).

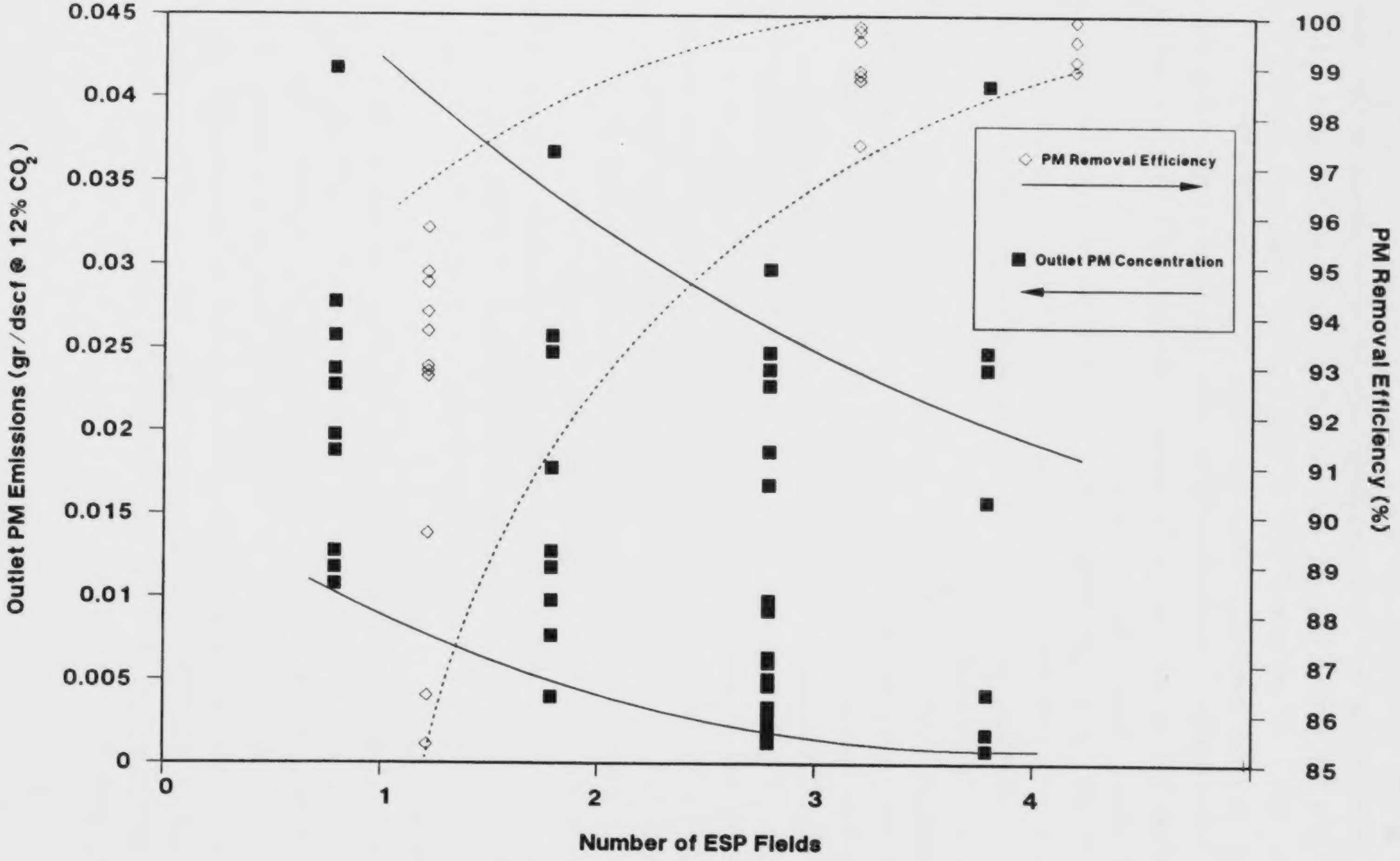


Figure 2-14. PM removal efficiency and outlet concentration as a function of the number of ESP fields.

generally state-of-the-art units designed for that level of outlet PM. All of the 3-field ESP's that did not achieve 0.01 gr/dscf were designed and operated to meet a PM emission limit of 0.03 gr/dscf. However, the SCA's of these ESP's were not generally lower than those of the 3-field ESP's achieving 0.01 gr/dscf. The 4-field ESP's were installed on RDF-fired MWC's and were permitted to achieve a 0.03 gr/dscf emission limit (Niagara Falls) or a limit of 0.1 gr/dscf (NSP Red Wing).

Nine of the ten 3- and 4-field ESP's for which PM removal efficiency was measured achieved a PM emission reduction efficiency of 98.7 percent or greater. In addition, an increase in PM removal efficiency with increases in the number of fields is observed.

The Deutsch-Anderson equation (discussed in Section 2.1) states that PM collection efficiency increases with SCA. As discussed for individual ESP's in Section 2.2, however, changes in flue gas flow rate and SCA at the individual facilities tested are generally too small to observe this relationship. Figure 2-15 is a graph of removal efficiency as a function of actual SCA for all of the facilities tested and discussed in Section 2.2 for which removal efficiency data are available. With the exception of Oswego County, which has a 1-field ESP, all of the ESP's shown on the figure have 3- or 4-fields. These data show that high PM removal efficiencies can be obtained with SCA's of 200 to greater than 600 $ft^2$/1,000 acfm.

Figure 2-16 shows outlet PM concentration as a function of design SCA. There is no consistent trend observed with the data. At SCA's from 200 to greater than 600 $ft^2$/1,000 acfm, PM concentrations of less than 0.005 to about 0.020 gr/dscf can be obtained.

Figure 2-17 shows the relationship between inlet and outlet PM concentrations. This plot is based on the data from individual test runs presented in Section 2.2. Note that the outlet PM concentrations from individual ESP's do not increase as a function of inlet PM concentration. For example, outlet PM concentrations at Peekskill were between 0.009 and 0.019 gr/dscf at ESP inlet concentrations ranging from 0.3 to 2.7 gr/dscf. Outlet PM concentrations of less than 0.01 gr/dscf were achieved by several ESP's with inlet PM concentrations from 0.4 to over 2.0 gr/dscf.

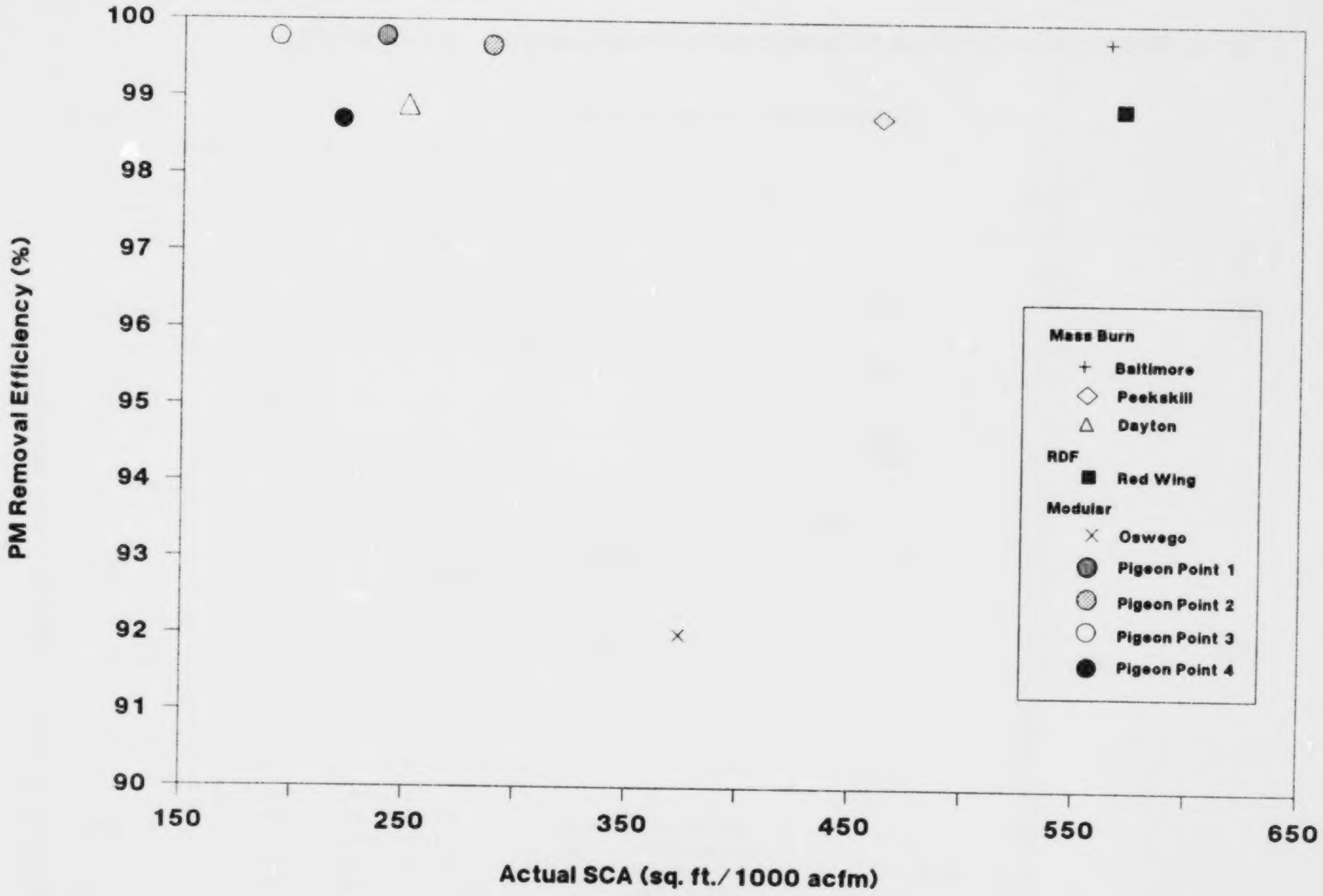
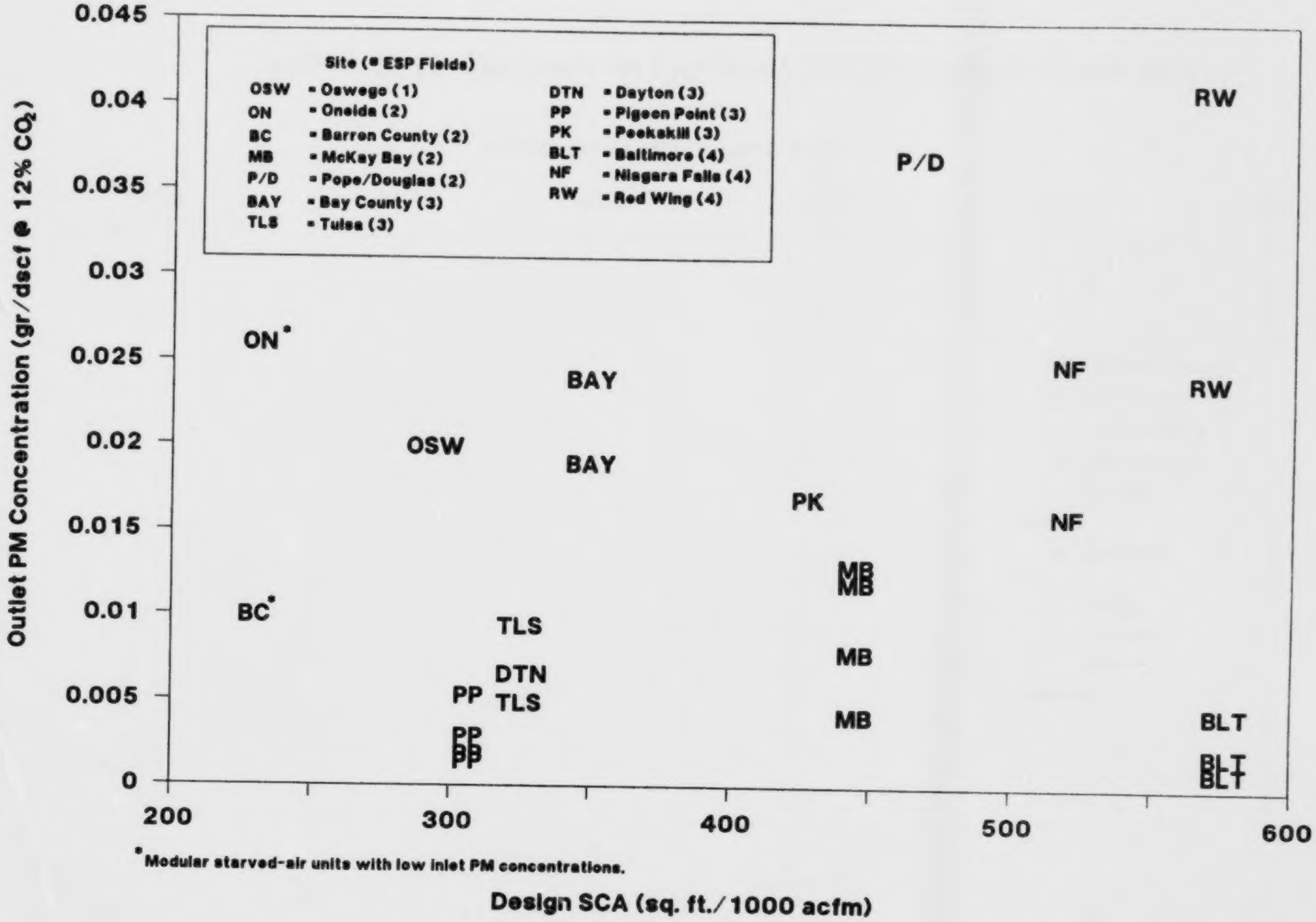


Figure 2-15. PM removal efficiency as a function of actual SCA.



*Modular starved-air units with low inlet PM concentrations.

Figure 2-16. Outlet PM concentration as a function of design SCA.

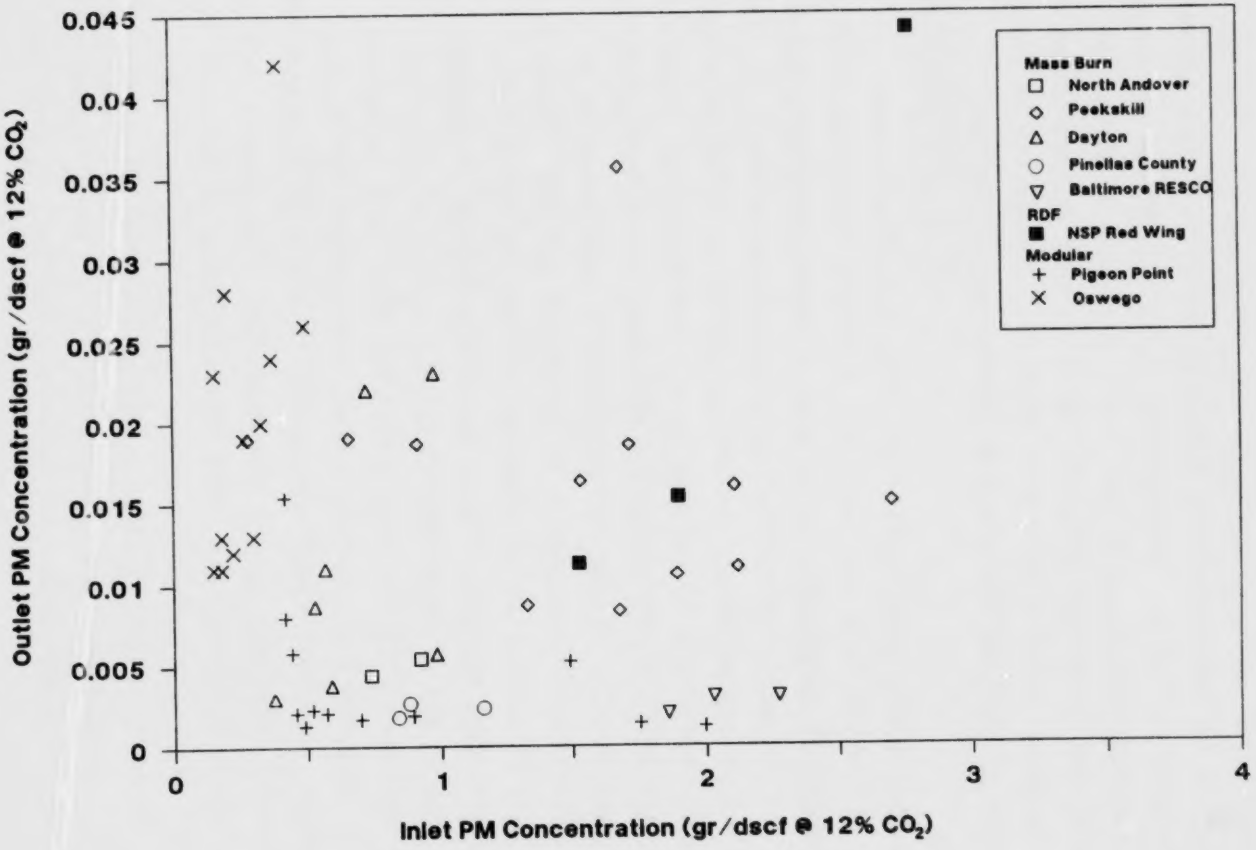


Figure 2-17. Relationship between ESP inlet and outlet PM concentrations.

These data demonstrate that PM emissions of 0.03 gr/dscf at 12 percent $CO_2$ are achievable by existing ESP's over a range of the number of fields, SCA, and inlet PM concentrations. It is not possible, however, to predict ESP performance based solely on the number of fields and SCA. The key factors affecting ESP performance not accounted for by the above parameters are the uniformity of flue gas distribution across the ESP and the design of the ESP's plate/electrode geometry that limits bypass of PM around the ionizing fields and collection surfaces. Because these factors cannot be changed during normal rebuild and repair of an ESP, the ability to increase the performance of existing ESP's to 0.01 gr/dscf may be limited.

### 2.3.2 Metals

Only limited metals removal efficiency data with simultaneous measurements at the ESP inlet and outlet are available (Baltimore RESCO and Dayton). However, it is possible to estimate a removal efficiency based on typical uncontrolled metals concentrations presented in Section 1.2. Because uncontrolled metals concentrations are fairly similar at different sites, the estimated removal efficiency is believed to be representative. Figures 2-18 and 2-19 show the metal and PM collection efficiency for individual ESP's discussed in Section 2.2. Figure 2-18 covers ESP's with estimated or measured PM collection efficiencies of 98 percent or greater. Figure 2-19 covers ESP's with PM collection efficiencies of less than 98 percent. Mercury is not included on either figure due to the absence of mercury removal occurring at any of these facilities.

As shown in Figure 2-18, for high efficiency ESP's with collection efficiencies of 98 percent or greater, removal efficiencies for arsenic, cadmium, chromium, lead, and nickel were generally from 0 to 3 percent less than the PM removal efficiency at the same facility. This suggests a high association of these metals with PM, with some enrichment of metals on the particulate that is less efficiently captured by high efficiency ESP's.

For ESP's with PM collection efficiencies of less than 98 percent, metals removals show somewhat more scatter, with collection efficiencies for individual metals being both higher and lower than for PM. As with high

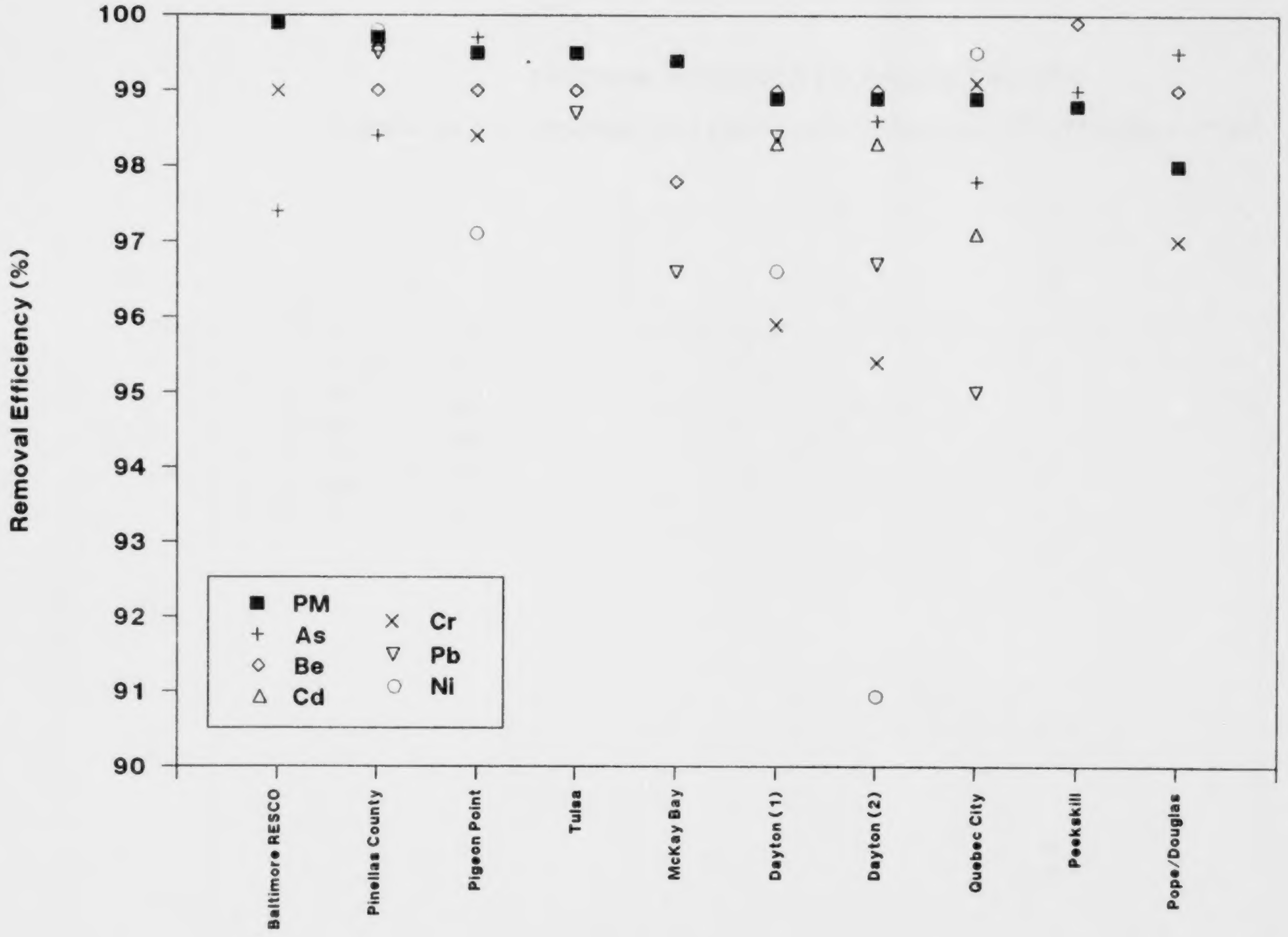


Figure 2-18. Metals and PM removal efficiency for ESP's with PM removal efficiency above 98 percent.

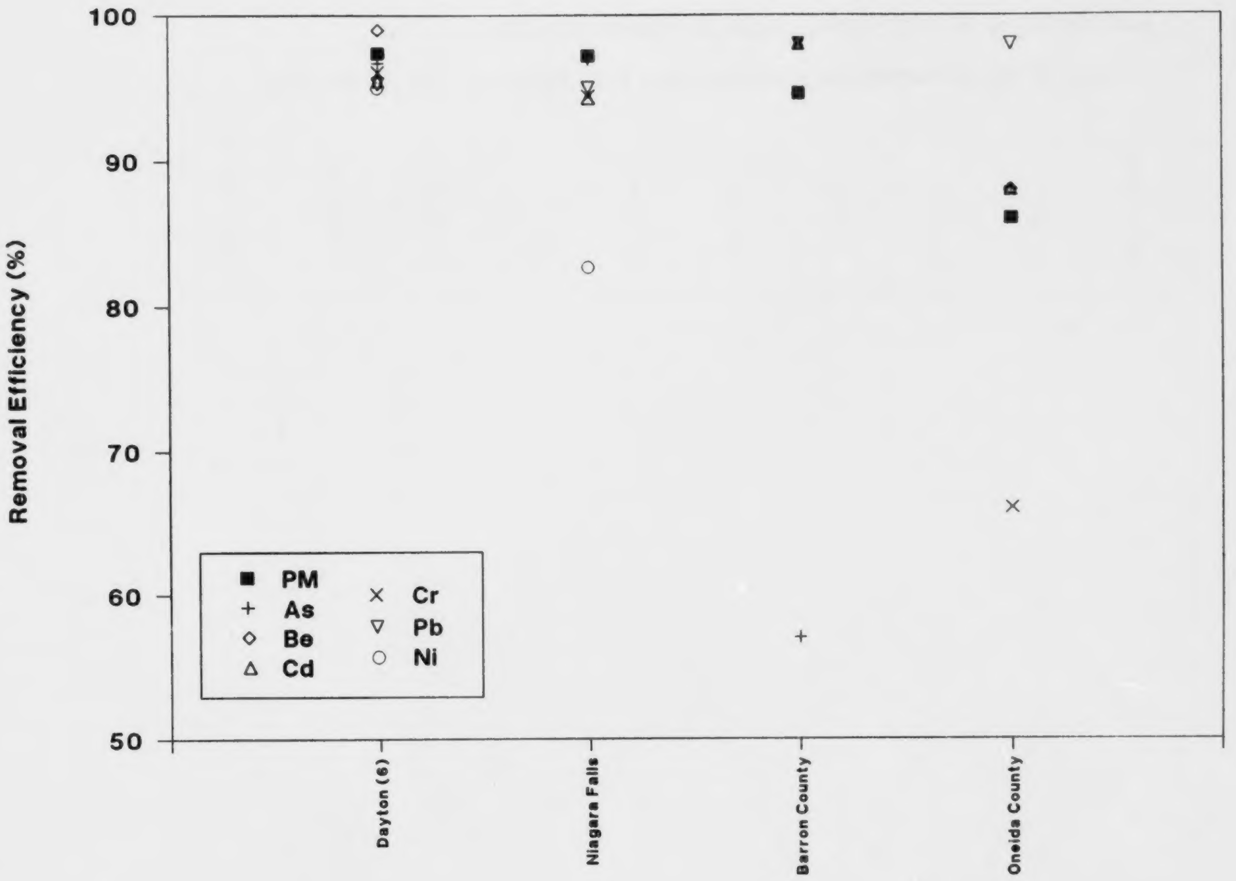


Figure 2-19. Metals and PM removal efficiency for ESP's with removal efficiency below 98 percent.

efficiency ESP's, however, there is a strong association between PM and metals collection efficiencies. In most of these instances, metals collection efficiencies from these units exceeded 90 percent.

For metals other than mercury, the control of PM emissions will also achieve reductions in metal emissions. If the PM removal efficiency is 98 percent or greater, the removal efficiency for arsenic, beryllium, cadmium, chromium, lead, or nickel will generally be at least 95 percent. Mercury is not removed by an ESP.

### 2.3.3 CDD/CDF

Outlet CDD/CDF concentrations have been measured at 13 MWC facilities with ESP's. Average ESP outlet concentrations ranged from 33 to 17,000 ng/dscm at 7 percent $O_2$. Emissions averaging less than 500 ng/dscm were measured at 10 of the 13 facilities. Inlet and outlet CDD/CDF concentrations were measured at five MWC's with ESP's. Three (Pinellas County, North Andover, and Peekskill) are mass burn waterwall units with heat recovery systems upstream of the ESP; one (Oswego County) is a modular starved-air unit with heat recovery; and one (Dayton) is a mass burn refractory wall unit with a spray quench chamber (no heat recovery) upstream of the ESP for flue gas cooling. Outlet emissions were higher than inlet emissions at four of these facilities, indicating formation across the ESP. The fifth facility (Peekskill) had lower outlet than inlet emissions, and thus had positive removal efficiency. An analysis of all five data sets indicates that ESP operating temperature is the principal parameter that affects performance on CDD/CDF emissions.

Figure 2-20 presents a plot of CDD/CDF removal efficiency as a function of ESP inlet temperature for the data from the four facilities with heat recovery systems upstream of the ESP. The data suggest increased CDD/CDF removal (less formation) for decreasing temperature. The temperatures evaluated range from 430 to 590°F, which include temperatures below which CDD/CDF formation is hypothesized to occur (450 to 650°F). Excluding Peekskill, higher outlet CDD/CDF concentrations than inlet (negative removal efficiency) are observed for 20 of 21 data points between 460 and 590°F. The Peekskill data, collected at ESP inlet temperatures of 435 to 479°F, are the only data set to have consistently positive CDD/CDF removal efficiency.

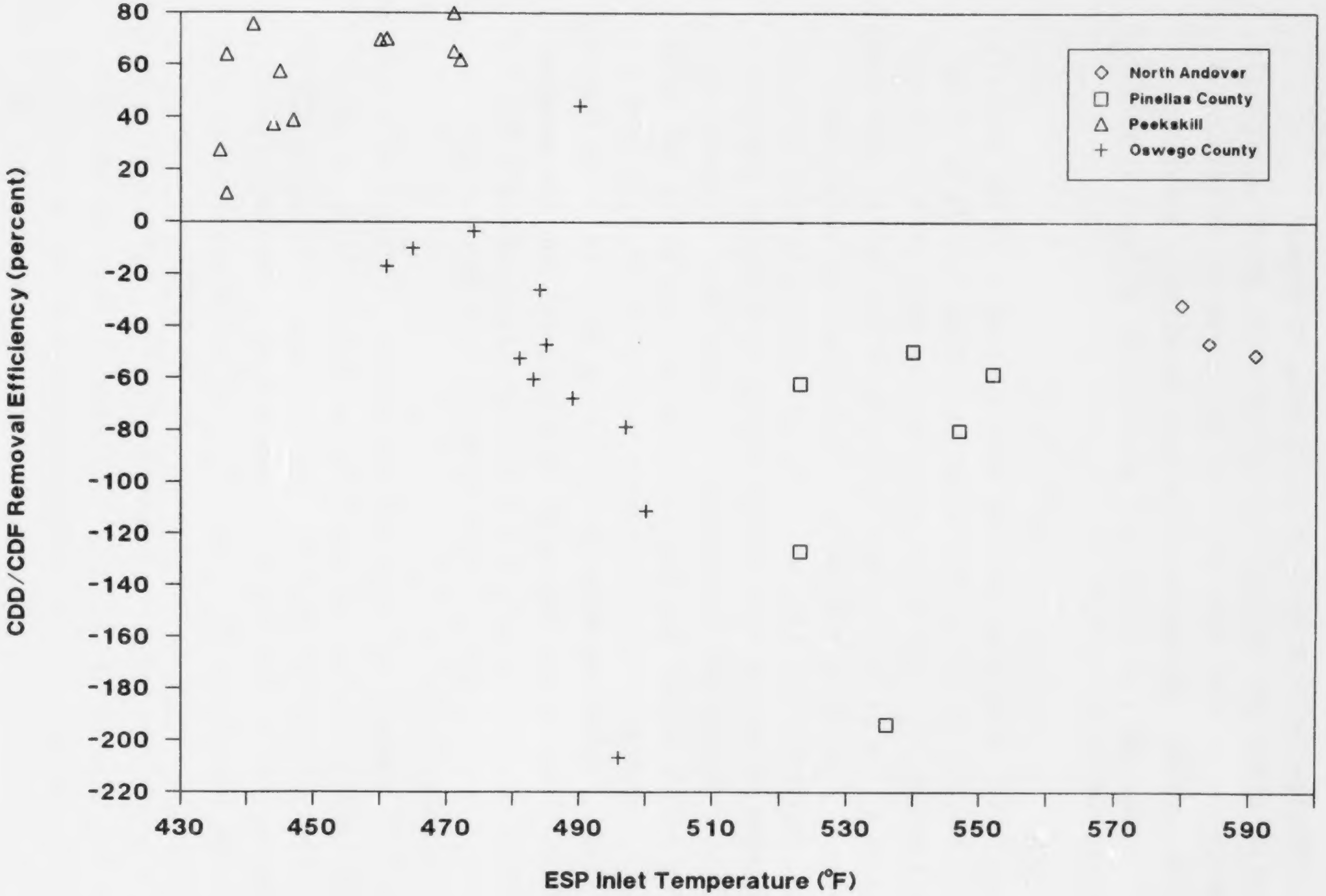


Figure 2-20. CDD/CDF removal efficiency as a function of ESP inlet temperature at MWC's with ESP's.

Thus, although there is no clear distinction, the data suggest that around 470$^{0}$F or less, positive removal can be achieved.

The Dayton results are not included in Figure 2-20 because the MWC is a refractory unit and uses a spray quench chamber rather than heat recovery for flue gas cooling. Results for Dayton are shown in Figure 2-21. The quench chamber both cools the flue gas and removes most of the larger PM particles. Some removal of CDD/CDF and HCl may also occur in the quench chamber. The rapid cooling of flue gas in the quench chamber may limit reaction time at temperatures required for CDD/CDF formation prior to the ESP. As a result, the ESP inlet CDD/CDF concentrations are relatively low, and are 80 to 90 percent lower than measured upstream at the mixing chamber. However, in the ESP, sufficient residence time, surface area, and temperature are apparently available to promote formation of CDD/CDF, as evidenced by increases in CDD/CDF concentration of 300 to 20,000 ng/dscm across the ESP. Because of the differences between Dayton and MWC's with heat recovery systems, the CDD/CDF data from Dayton may not be comparable with the data from the other MWC's.

As with MWC's with heat recovery, however, reductions in ESP operating temperature at Dayton reduced outlet CDD/CDF concentrations as shown in Figure 2-21. By decreasing the ESP inlet temperature from 575 to 400$^{0}$F, outlet CDD/CDF concentrations decrease from 17,000 ng/dscm to 1,000 ng/dscm. This is a similar trend to that observed in Figure 2-20, suggesting that a decrease in temperature at the ESP inlet will improve ESP performance for CDD/CDF.

The inlet CDD/CDF concentration may have a secondary effect on performance, but the data are inconclusive. There is no apparent effect of inlet PM concentrations on performance.

Based on analysis of the available data, ESP performance for CDD/CDF can be improved by lowering the ESP inlet temperature. For MWC's with heat recovery, limiting ESP inlet temperature to 450$^{0}$F or less appears to eliminate formation of CDD/CDF across the ESP.

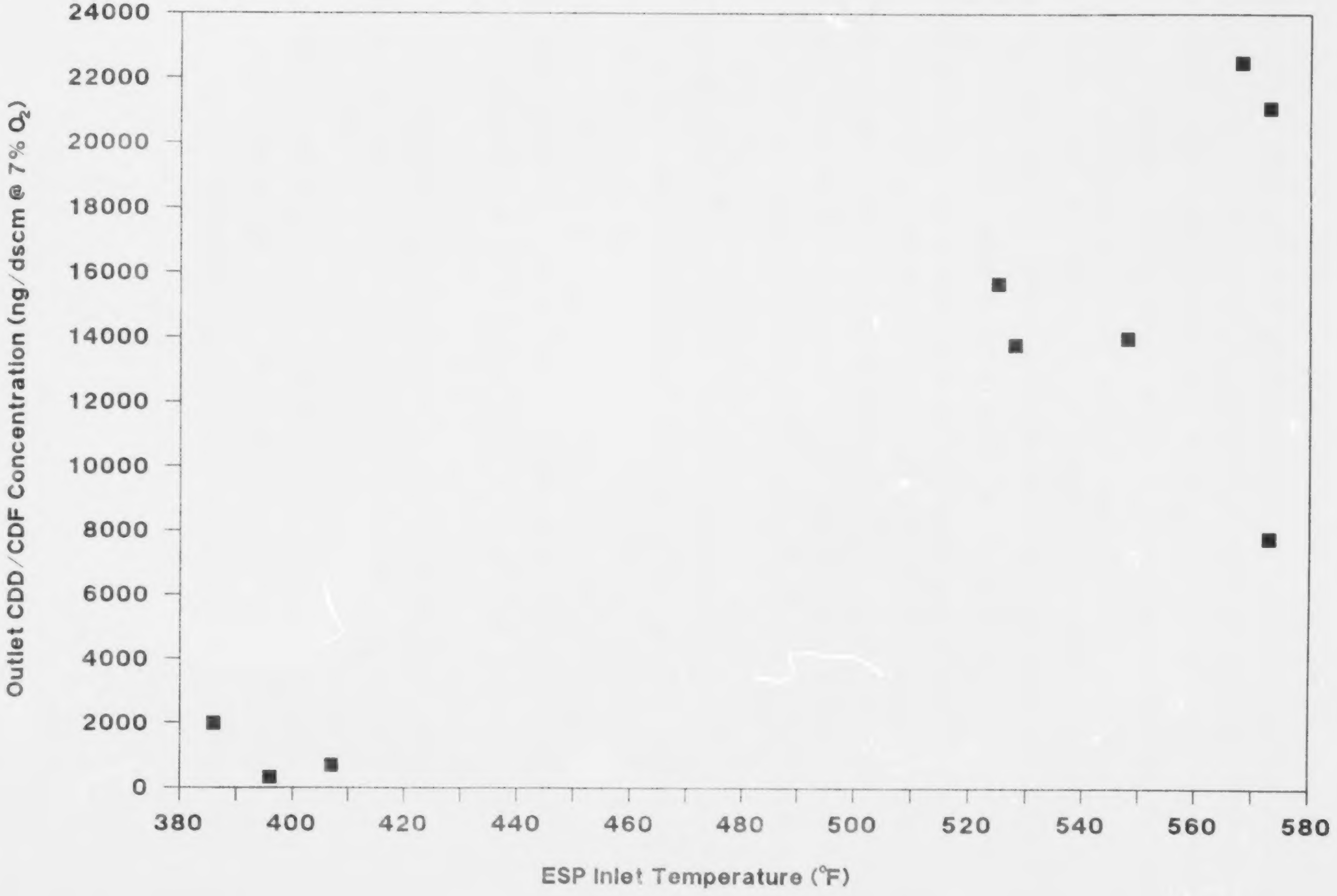


Figure 2-21. Outlet CDD/CDF concentration as a function of ESP inlet temperature at Dayton.

## 2.4 REFERENCES

1. Turner, J. H., P. A. Lawless, T. Yamamoto, D. W. Coy, G. P. Greiner, J. D. McKenna, and W. M. Vatavuk. Sizing and Costing of Electrostatic Precipitators (Part I. Sizing Considerations). Journal of Air Pollution Control and Waste Management (JAPCA). April 1988. pp. 459-460.

2. Reference 1, pp. 458-459.

3. Sedman, C. B., and T. G. Brna. Municipal Waste Combustion Study: Flue Gas Cleaning Technology. U. S. Environmental Protection Agency, Research Triangle Park, NC. EPA Publication No. EPA/530-SW87-021d. June 1987. pp. 2-3 to 2-4.

4. California Air Resources Board. Air Pollution Control at Resource Recovery Facilities. Sacramento, CA, May 24, 1984. pp. 153-156.

5. Reference 4, pp. 147-151.

6. Vogg, H., and L. Stieglitz. Chemosphere. 1986. Vol. 15, p. 1373.

7. Zurlinden, R. A., et. al., (Ogden Projects, Inc.). Environmental Test Report, Alexandria/Arlington Resource Recovery Facility, Units 1, 2, and 3. (Prepared for Ogden Martin Systems of Alexandria/Arlington, Inc.) Alexandria, VA. Report No. 144 A (Revised). January 1988.

8. Entropy Environmentalists, Inc. Baltimore RESCO Company, L. P., Southwest Resource Recovery Facility. Particulate, Sulfur Dioxide, Nitrogen Oxides, Chlorides, Fluorides, and Carbon Monoxide Compliance Testing, Units 1, 2, and 3. (Prepared for RUST International, Inc.) January 1985.

PEI Associates, Inc. Method Development and Testing for Chromium, No. 2 Refuse-to-Energy Incinerator, Baltimore RESCO. (Prepared for U. S. Environmental Protection Agency. Research Triangle Park, NC. EMB Report 85-CHM8. EPA Contract No. 68-02-3849. August 1986.

Beachler, D. S., et. al. (Westinghouse Electric Corporation). Bay County, Florida, Waste-to-Energy Facility Air Emission Tests. Presented at Municipal Waste Incineration Workshop, Montreal, Canada. October 1987.

Radian Corporation. Preliminary Test Data from October-November 1988 Testing at the Montgomery County South Plant, Dayton, Ohio.

Clean Air Engineering, Inc. Report on Compliance Testing for Waste Management, Inc. at the McKay Bay Refuse-to-Energy Project located in Tampa, FL. October 1985.

13. Campbell. J., Chief, Air Engineering Section, Hillsborough County Environmental Protection Commission, to Martinez, E. L., Source Analysi Section/AMTB, U. S. Environmental Protection Agency, May 1, 1986.

14. Telecon. Weigle, G., McKay Bay Refuse-to-Energy Project, with Vancil, M. A., Radian Corporation. April 7, 1988. Specific collecting area of ESP.

15. Anderson, C. L., et. al. (Radian Corporation). Summary Report, CDD/CDF, Metals and Particulate, Uncontrolled and Controlled Emissions, Signal Environmental Systems, Inc., North Andover RESCO, North Andover, MA. (Prepared for U. S. Environmental Protection Agency. Research Triangle Park, NC. EMB Report No. 86-MIN02A. EPA Contract No. 68-02-4338. March 1988.

16. Fossa, A. J., et. al. Phase I Resource Recovery Facility Emission Characterization Study, Overview Report. New York State Department of Environmental Conservation. Albany, NY. May 1987.

17. Radian Corporation. Results from the Analysis of MSW Incinerator Testing at Peekskill, New York (DRAFT). (Prepared for the New York State Energy Research and Development Authority). Albany, NY. March 1988.

18. Entropy Environmentalists, Inc. Stationary Source Sampling Report, Signal RESCO, Pinellas County Resource Recovery Facility, St. Petersburg, Florida, CARB/DER Emission Testing, Unit 3 Precipitator Inlets and Stack. February and March 1987.

19. Lavalin, Inc. National Incinerator Testing and Evaluation Program: The Combustion Characterization of Mass Burning Incinerator Technology; Quebec City (DRAFT). (Prepared for Environmental Protection Service, Environmental Canada). Ottowa, Canada. September 1987.

20. Seelinger, R., et. al. (Ogden Products, Inc.) Environmental Test Report, Walter B. Hall Resource Recovery Facility, Units 1 and 2. (prepared for Ogden Martin Systems of Tulsa, Inc.). Tulsa, OK. September 1986.

21. Knisley, D. R., et. al. (Radian Corporation). Emissions Test Report, Dioxin/Furan Emission Testing, Refuse Fuels Associates, Lawrence MA. (Prepared for Refuse Fuels Association). Haverhill, MA. June 1987.

22. Entropy Environmentalists, Inc. Stationary Source Sampling Report, Ogden Martin Systems of Haverhill, Inc., Lawrence, Massachusetts Thermal Conversion Facility. Particulate, Dioxins/Furans and Nitrogen Oxides Emission Compliance Testing. September 1987.

23. Preliminary Report on Occidental Chemical Corporation EFW. New York State Department of Environmental Conservation. Albany, NY. January 1986.

24. Trip Report, Occidental Chemical Corporation EFW in Niagara Falls, NY. Epner, E., Radian Corporation. December 1987. Attachments.

25. H. J. Hall, Associates. Summary Analysis on Precipitator Tests and Performance Factors, May 13-15, 1986 at Incinerator Units 1, 2 - Occidental Chemical Company. Prepared for Occidental Chemical Company EFW. Niagara Falls, NY. June 25, 1986.

26. Interpoll Laboratories. Results of the March 21 - 26, 1988, Air Emission Compliance Test on the No. 2 Boiler at the Red Wing Station, Test IV (High Load). Prepared for Northern States Power Company, Minneapolis, Minnesota. Report No. 8-2526. May 10, 1988.

27. Interpoll Laboratories. Results of the May 24 - 27, 1988 High Load Compliance Test on Unit 1 and Low Load Compliance Test on Unit 2 at the NSP Red Wing Station. Prepared for Northern States Power Company. Minneapolis, Minnesota. Report No. 8-2559. July 21, 1988.

28. Memorandum. Perez, Joseph, AM/3, State of Wisconsin, to Files. Review of Stack Test Performed at Barron County Incinerator. February 24, 1987.

29. Reference 16.

30. Telecon. DeVan, S. Oneida ERF, with Vancil, M. A., Radian Corporation. April 4, 1988. Specific collecting area of ESP's.

31. Radian Corporation. Data Analysis Results for Testing at a Two-Stage Modular MSW Combustor: Oswego County ERF, Fulton, NY. Prepared for New York State's Energy Research and Development Authority. Albany, NY. November 1988.

32. Letter with attachments from Gehring, Philip, Plant Manager (Pigeon Point Energy Generating Facility), to Farmer, Jack R., Director, ESD, OAQPS, U. S. Environmental Protection Agency. June 30, 1988.

33. Interpoll Laboratories. Results of the July 1987 Emission Performance Tests of the Pope/Douglas Waste-to-Energy Facility MSW Incinerators in Alexandria, MN. (Prepared for HDR Techserv, Inc.). Minneapolis, MN. October 1987.

34. Telecon. Chamberlain, L., Minnesota Pollution Control Agency, with Vancil, M. A., Radian Corporation. March 30, 1988. Specific collection area of ESP's at Pope/Douglas.

# 3.0 FURNACE SORBENT INJECTION

Section 3 describes the technology and performance of furnace sorbent injection (FSI) systems with an ESP for PM control as applied to MWC facilities. No data are available for FSI systems followed by a FF for PM control as applied to MWC facilities. In Section 3.1, operation and design of FSI systems are described. Section 3.2 describes MWC facilities equipped with FSI/ESP systems for which emissions data are available and summarizes the available emissions test data. In Section 3.3, the performance of FSI/ESP systems relative to the control of acid gas, PM, metals, and CDD/CDF emissions is described.

## 3.1 PROCESS DESCRIPTION

Furnace sorbent injection is a technique for controlling acid gas emissions which has been applied to conventional and fluidized bed MWC's. Lime (CaO) or limestone ($CaCO_3$) is injected into the furnace section of the MWC. If limestone is used, sufficient temperature must be available for calcination of $CaCO_3$ to CaO and $CO_2$. Limestone is rapidly calcined to lime in the furnace at temperatures of 1,400 to 2,000$^{o}$F. The lime, in turn, reacts with $SO_2$ and HCl to form calcium sulfate ($CaSO_4$) and calcium chloride ($CaCl_2$), which can be removed by the PM control device. In conventional MWC's, sorbent can be injected into the furnace using existing overfire air jets or through separate ports located above the fuel bed. In fluidized bed combustors, the sorbent is injected either into or above the fuel bed.

Furnace sorbent injection provides for effective $SO_2$ removal because lime and $SO_2$ readily react at typical furnace temperatures of 1,600 to 2,200$^{o}$F. Furnace sorbent injection also provides extended contact time between lime and acid gases, as they are in contact in the flue gas starting in the combustor, through the heat recovery sections, and ending in the particulate control device. Furnace sorbent injection can also potentially reduce CDD/CDF formation by removing chlorine prior to chlorination of CDD/CDF. However, HCl and lime reportedly do not react at temperatures above 1,400$^{o}$F.[1] Potential disadvantages of FSI include fouling and erosion of convective heat transfer surfaces by the injected sorbent.

Use of FSI will increase the PM loading to the particulate control device. Because of this, a particulate control device needs to be sized larger than if FSI were not used. However, the characteristics of the PM are not changed sufficiently by injection of sorbent to affect the ability of the control device to remove particulate matter. Operation and design of ESP's is described in Section 2.1. Fabric filter design and operation is discussed in Section 4.1.

## 3.2 SUMMARY OF TEST DATA

Section 3.2 presents the available emissions data for MWC facilities equipped with furnace sorbent injection systems followed by an ESP. A description of the facility and a summary and analysis of the emissions data are provided for each facility. The data presented in this section are based on short-term testing (less than 3 hours). Although either an ESP or fabric filter can be used as the PM control device, data are available only from systems with an ESP.

The effects of stoichiometric ratio and ESP inlet temperature on acid gas removal are discussed in each section. The effect of SCA on PM removal and the effect of ESP inlet temperature on CDD/CDF removal are discussed as well.

Because simultaneous measurements of uncontrolled and controlled acid gases cannot be made at MWC's using furnace sorbent injection, removal efficiencies for acid gases cannot be directly calculated. However, acid gas removal efficiencies for a given MWC are estimated based on typical acid gas concentrations at that MWC operating without FSI if those data are available or based on typical uncontrolled acid gas emission levels (see Section 1.2).

### 3.2.1 Alexandria.[2,3]

The Alexandria/Arlington Resource Recovery Facility in Alexandria, Virginia, consists of three identical 325 ton/day Martin GmbH waterwall combustors. Emissions from each combustor are controlled with a 3-field ESP. The flue gas temperature at the ESP outlet is generally about 340$^{o}$F with a gas flow of about 67,000 acfm (40,000 dscfm). The ESP's are designed to meet a PM emission limit of 0.03 gr/dscf at 12 percent $CO_2$. Dry hydrated lime can be injected into the combustor with the overfire air for acid gas control and has been used on these combustors since startup in January 1987.

In December 1987, tests were performed to demonstrate compliance with operating permits. The tests were conducted under normal operating conditions with dry hydrated lime injection on Unit 1 and without lime injection on Units 2 and 3. The tests with lime injection are reported here. The tests without lime addition are reported in Section 2.2.1.1. The hydrated lime feed rate during testing was 150 lb/hr. Flue gas was sampled at the ESP outlet for $SO_2$, HCl, PM, $NO_x$, and CDD/CDF.

Acid gas data are presented in Table 3-1. Acid gases were measured at the ESP outlet of Unit 1 only. Outlet $SO_2$ concentrations ranged from 32 to 45 ppm at 7 percent $O_2$ over three runs and averaged 37 ppm. Assuming a typical uncontrolled $SO_2$ concentration of 200 ppm (see Section 1.2), approximately 80 percent $SO_2$ removal occurred. Outlet HCl concentrations ranged from 148 to 200 ppm at 7 percent $O_2$ and averaged 166 ppm. Based on a typical uncontrolled HCl concentration of 500 ppm (see Section 1.2), 60 - 70 percent HCl removal occurred. Because uncontrolled $SO_2$ and HCl concentrations cited above were not measured, the actual stoichiometric ratio could not be evaluated. However, based on typical uncontrolled $SO_2$ and HCl concentrations cited above, the hydrated lime feed rate of 150 lb/hr corresponds to a stoichiometric ratio of about 0.9. The temperature at the ESP inlet varied over a limited range (366 to 373$^{o}$F), preventing analysis of the effect of this parameter on FSI/ESP performance.

In Table 3-2, particulate data from testing with furnace sorbent injection are presented. Flue gas flow rate and temperature were relatively constant for all three runs. Outlet PM emissions ranged from 0.016 to 0.035 gr/dscf and averaged 0.024 gr/dscf. Particulate data for Alexandria without furnace sorbent injection are presented in Section 2.2.1. Without FSI, outlet PM emissions averaged 0.027 gr/dscf. Therefore, the use of FSI did not detrimentally affect ESP performance during the tests.

In Table 3-3, CDD/CDF data are presented. Outlet CDD/CDF emissions ranged from 52 to 59 ng/dscm and averaged 55 ng/dscm. Uncontrolled CDD/CDF emissions were not measured. However, other combustors with Martin GmbH grates have demonstrated low uncontrolled CDD/CDF emissions (e.g., Marion County with 40 ng/dscm [Section 7.2.5] and Pinellas County with 54 ng/dscm

## TABLE 3-1. ACID GAS DATA FOR ALEXANDRIA WITH LIME INJECTION

| Test Condition | Run Numbers | ESP Inlet Temperature[a] (°F) | Stoichiometric Ratio | Outlet Acid Gas Concentrations (ppm, dry at 7% $O_2$) | |
|---|---|---|---|---|---|
| | | | | $SO_2$ | HCl |
| Combustor = Normal | 1 | 366 | NM[b] | 45 | 200 |
| FSI/ESP = Normal | 2 | 364 | NM | 34 | 150 |
| | 3 | 373 | NM | 32 | 148 |
| Average | | 368 | 0.9[c] | 37 | 166 |

[a] Temperatue estimated from a measured value at the stack and an assumed temperature drop across the ESP (20°F).

[b] NM = Not measured.

[c] Estimated from known lime feed rate of 150 lb/hr and assumed inlet $SO_2$ and HCl concentrations of 200 and 500 ppm (see Section 1.2), respectively.

## TABLE 3-2. PARTICULATE DATA FOR ALEXANDRIA WITH LIME INJECTION

| Test Condition | Run Number | ESP Inlet Temperature[a] (°F) | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1 | 366 | 70,196 | 0.016 |
| FSI/ESP = Normal | 2 | 364 | 67,605 | 0.035 |
|  | 3 | 373 | 73,376 | 0.022 |
| Average |  | 368 | 70,392 | 0.024 |

[a] Temperature estimated from measured value at the stack and an assumed temperature drop across the ESP (20°F).

## TABLE 3-3. CDD/CDF DATA FOR ALEXANDRIA WITH LIME INJECTION

| Test Condition | Run Number | ESP Inlet Temperature[a] (°F) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1 | 358 | 51.8 |
| FSI/ESP = Normal | 2 | 364 | 53.8 |
|  | 3 | 364 | 59.0 |
| Average |  | 362 | 54.9 |

[a] Temperature estimated from measured value at the stack and an assumed temperature drop across the ESP (20°F).

[Section 2.2.1.8]), suggesting that injection of hydrated lime into the furnace combined with ESP operation at 360°F, resulted in little or no net effect on the control of CDD/CDF emissions.

### 3.2.2 Dayton[4]

The Montgomery County South incinerator plant in Dayton, Ohio includes three nearly identical Volund refractory-lined combustors. Emissions are controlled with ESP's. A complete description of the facility is provided in Section 2.2.1.4.

In November and December 1988, testing was conducted by EPA on Unit 3. Tests were conducted with furnace sorbent injection, duct sorbent injection, and without sorbent injection. A complete description of the test program is provided in Section 2.2.1.4. The results from the tests with furnace sorbent injection are reported here. The results from tests without sorbent injection are reported in Section 2.2.1.4. The results of tests with duct sorbent injection are reported in Section 4.2.1.

Acid gas data from the screening and parametric tests are presented in Table 3-4. A total of 30 test runs were conducted under a variety of sorbent feed rates and ESP inlet temperatures. It should be noted in reviewing the data that the water spray in the quench chamber provided some removal of HCl from the flue gas. Also, high stoichiometric ratios were used, which are not typical of normal operation. Thus, the performance demonstrated at Dayton may not be indicative of a system under commercial operation.

In addition, because limestone is injected directly into the furnace, it is not possible to measure uncontrolled acid gas concentrations and calculate removal efficiency. Therefore, typical uncontrolled concentrations of 500 ppm for HCl and 200 ppm for $SO_2$ are assumed. (See Section 1.2.)

Finally, because the true stoichiometric ratio could not be determined for each test, the effect of this parameter is not evaluated. Instead, the effect of limestone feed rate on system performance is evaluated. Variations in temperature while maintaining in limestone feed rate allow evaluation of the effect of temperature on system performance.

TABLE 3-4. ACID GAS DATA FOR DAYTON WITH FURNACE SORBENT INJECTION

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Stoichiometric Ratio[a] | Acid Gas Concentration (ppm, dry at 7% $O_2$) | | | |
|---|---|---|---|---|---|---|---|
| | | | | ESP Inlet | | ESP Outlet | |
| | | | | $SO_2$ | HCl | $SO_2$ | HCl |
| Combustor = Normal | P10 | 397 | 3.3 | 97.0 | NM[b] | 90.0 | 218 |
| FSI= 500 lb/hr | P11 | 391 | 3.3 | 19.8 | NM | 34.0 | 80.3 |
| ESP = 400°F inlet | P12 | 395 | 3.3 | 28.5 | NM | 48.1 | 62.8 |
| Average | | 394 | 3.3 | 48.4 | NM | 57.4 | 120 |
| Combustor = Normal | P13 | 297 | 3.3 | 15.9 | NM | 21.6 | 11.5 |
| FSI = 500 lb/hr | P13A | 297 | 3.3 | 11.6 | NM | 21.1 | NM |
| ESP = 300°F inlet | P14 | 301 | 3.3 | 62.3 | NM | 31.1 | 79.5 |
| | P14A | 301 | 3.3 | 18.5 | NM | 17.7 | NM |
| | P15 | 296 | 3.3 | 4.5 | NM | 19.1 | 13.6 |
| | P15A | 296 | 3.3 | 9.3 | NM | 14.5 | NM |
| Average | | 298 | 3.3 | 20.3 | NM | 20.8 | 34.9 |
| Combustor = Low mixing | S8A | 550 | 1.6 | 192 | 152 | NM | NM |
| chamber temp. (1550°F) | S8B | 550 | 1.6 | 201 | 168 | NM | NM |
| FSI = 250 lb/hr | S8C | 550 | 1.6 | 103 | 180 | NM | NM |
| ESP = 550°F inlet | | | | | | | |
| Average | | 550 | 1.6 | 165 | 167 | NM | NM |
| Combustor = Low mixing | S5A | 550 | 1.6 | 72.5 | 141 | 46.8 | NM |
| chamber temp. (1600°F) | S5B | 550 | 1.6 | NM | 197 | 52.9 | NM |
| FSI = 250 lb/hr | S5C | 550 | 1.6 | NM | 211 | 37.5 | NM |
| ESP = 550°F inlet | | | | | | | |
| Average | | 550 | 1.6 | 72.5 | 183 | 45.7 | NM |
| Combustor = Normal | S6 | 550 | 1.6 | 76.6 | NM | 58.0 | NM |
| FSI = 250 lb/hr | S7 | 550 | 1.6 | 101 | NM | 77.1 | NM |
| ESP = 550°F inlet | | | | | | | |
| Average | | 550 | 1.6 | 88.6 | NM | 67.6 | NM |
| Combustor = Normal | S1A | 400 | 1.6 | 122 | 171 | NM | NM |
| FSI = 250 lb/hr | S1B | 400 | 1.6 | 113 | 193 | NM | NM |
| ESP = 400°F inlet | S1C | 400 | 1.6 | 128 | 173 | NM | NM |
| Average | | 400 | 1.6 | 124 | 179 | NM | NM |
| Combustor = Normal | S12 | 350 | 1.6 | 83.0 | 119 | NM | NM |
| FSI = 250 lb/hr | | | | | | | |
| ESP = 350°F inlet | | | | | | | |
| Combustor = Normal | S2A | 400 | 4.9 | 77.4 | 26.3 | NM | NM |
| FSI = 750 lb/hr | S2B | 400 | 4.9 | 75.4 | 73.1 | NM | NM |
| ESP = 400°F inlet | S2C | 400 | 4.9 | 45.5 | 35.4 | NM | NM |
| Average | | 400 | 4.9 | 66.1 | 44.9 | NM | NM |
| Combustor = Normal | S3A | 350 | 4.9 | 24.8 | 53.9 | NM | NM |
| FSI = 750 lb/hr | S3B | 350 | 4.9 | 51.6 | 43.0 | NM | NM |
| ESP = 350°F inlet | S3C | 350 | 4.9 | 35.0 | 41.4 | NM | NM |
| Average | | 350 | 4.9 | 37.1 | 46.1 | NM | NM |
| Combustor = Normal | S4A | 300 | 4.9 | 7.2 | 45.3 | NM | NM |
| FSI = 750 lb/hr | S4B | 300 | 4.9 | 20.3 | 39.4 | NM | NM |
| ESP = 300°F inlet | S4C | 300 | 4.9 | 15.4 | 92.1 | NM | NM |
| Average | | 300 | 4.9 | 14.3 | 58.9 | NM | NM |

[a] Stoichiometric ratio calculated using known limestone feed rate and typical uncontrolled $SO_2$ and HCl concentrations (200 ppm at 7 percent $O_2$ for $SO_2$ and 500 ppm at 7 percent $O_2$ for HCl).

[b] NM = Not measured.

The parametric tests involved FSI operation at a constant sorbent injection rate of 500 lb/hr with three test runs at an ESP inlet temperature of 400°F and six test runs at an ESP inlet temperature of 300°F. The ESP inlet $SO_2$ concentrations ranged from 4.5 ppm to 97 ppm over the nine test runs, averaging 48 ppm at an ESP inlet temperature of 400° and 20 ppm at an ESP inlet temperature of 300°F.

Assuming a typical uncontrolled $SO_2$ concentration of 200 ppm (see Section 1.2), the measured outlet $SO_2$ concentration during the parametric tests suggest removal efficiencies of 55 to 93 percent. The ESP outlet HCl concentrations ranged from 12 to 218 ppm over six test runs, averaging 120 ppm at an ESP inlet temperature of 400°F and 34.9 at an ESP inlet temperature of 300°F. HCl removal efficiencies of 56 to 98 percent are estimated assuming typical uncontrolled HCl concentrations of 500 ppm (see Section 1.2).

The screening tests involved FSI operations at sorbent injection rates of 250 and 750 lb/hr at four ESP inlet temperatures (550, 400, 350, and 300°F). A total of 12 test runs were conducted with 250 lb/hr of sorbent injected. Eight of these tests were conducted at an ESP inlet temperature of 550°F (three with 1550° mixing chamber temperature, three with 1600°F mixing chamber temperature, and two with normal [1800°F] mixing chamber temperature), three tests at an ESP inlet temperature of 400°F, and one test with a temperature of 350°. These last four tests were at normal mixing chamber temperatures. The ESP inlet $SO_2$ concentrations ranged from 72 to 200 ppm over all 12 runs and averaged 125 ppm at ESP inlet temperature of 550°F, 121 ppm at 400°F, and 83 ppm at 350°F. Based on the variability in run to run $SO_2$ measurements, no clear relationship between $SO_2$ levels and ESP temperature are apparent over this temperature range. At the ESP outlet, $SO_2$ concentrations averaged 54 ppm during the tests conducted at an ESP inlet temperature of 550°F. Data on $SO_2$ concentrations at the ESP outlet were not collected during the other tests. Based on a typical uncontrolled $SO_2$ concentrations of 200 ppm, these data suggest removal efficiencies of about 75 percent.

During these same test conditions, HCl concentrations at the ESP inlet ranged from 119 to 211 ppm and averaged 175 ppm at an ESP inlet temperature of 550°F, 179 ppm at an ESP inlet temperature of 400°F, and 119 ppm at an ESP inlet temperature of 350°F. Compared to a typical uncontrolled HCl concentration of 500 ppm, these measurements suggest HCl removal efficiencies of 50 to 80 percent, but no clear relationship with temperature.

Nine test runs were conducted at a sorbent injection rate of 750 lb/hr during the screening tests. The mixing chamber temperature was normal during all of these three runs. Three runs were conducted at each of three ESP inlet temperatures--400, 350, and 300°F. ESP inlet $SO_2$ concentrations ranged from 7.2 to 77 ppm and averaged 66, 37, and 14 ppm at ESP inlet temperatures of 400, 350, and 300°F, respectively. Compared to a typical uncontrolled $SO_2$ concentration of 200 ppm. These measured concentrations indicate removal efficiencies of 70 to 90 percent and suggest increased removal of $SO_2$ as ESP inlet temperatures are decreased over this range of temperatures.

Also with 750 lb/hr of sorbent, HCl concentrations at the ESP inlet ranged from 26 to 92 ppm and averaged 45, 46, and 59 ppm at 400, 350, and 300°F, respectively, at the ESP inlet. Compared to a typical uncontrolled HCl concentrations of 500 ppm, these HCl measurements indicate removal efficiencies of about 90 percent.

In Figure 3-1, $SO_2$ concentration at the ESP inlet is shown as functions of limestone feed rate and ESP inlet temperature. Concentrations measured when no sorbent was injected at Dayton are shown for comparison. Figure 3-2, plots HCl concentrations at the ESP inlet. Two effects are noteworthy from these plots. First, increasing lime feed rate decreases both $SO_2$ and HCl emissions. At limestone feed rates of 750 lbs/hr, $SO_2$ and HCl emissions are roughly one-half to one-third the levels measured at 250 lbs/hr of limestone and equivalent temperatures. Second, at ESP inlet temperatures of less than 400°F, decreasing ESP operating temperature results in lower $SO_2$ emissions. No similar relationship was noted between inlet HCl concentrations and ESP temperature. However, data collected at the ESP outlet during the parametric test, with a feed rate of 500 lb/hr of sorbent, show an HCl concentration of 120 ppm at 400°F and a concentration of 35 ppm at 300°F.

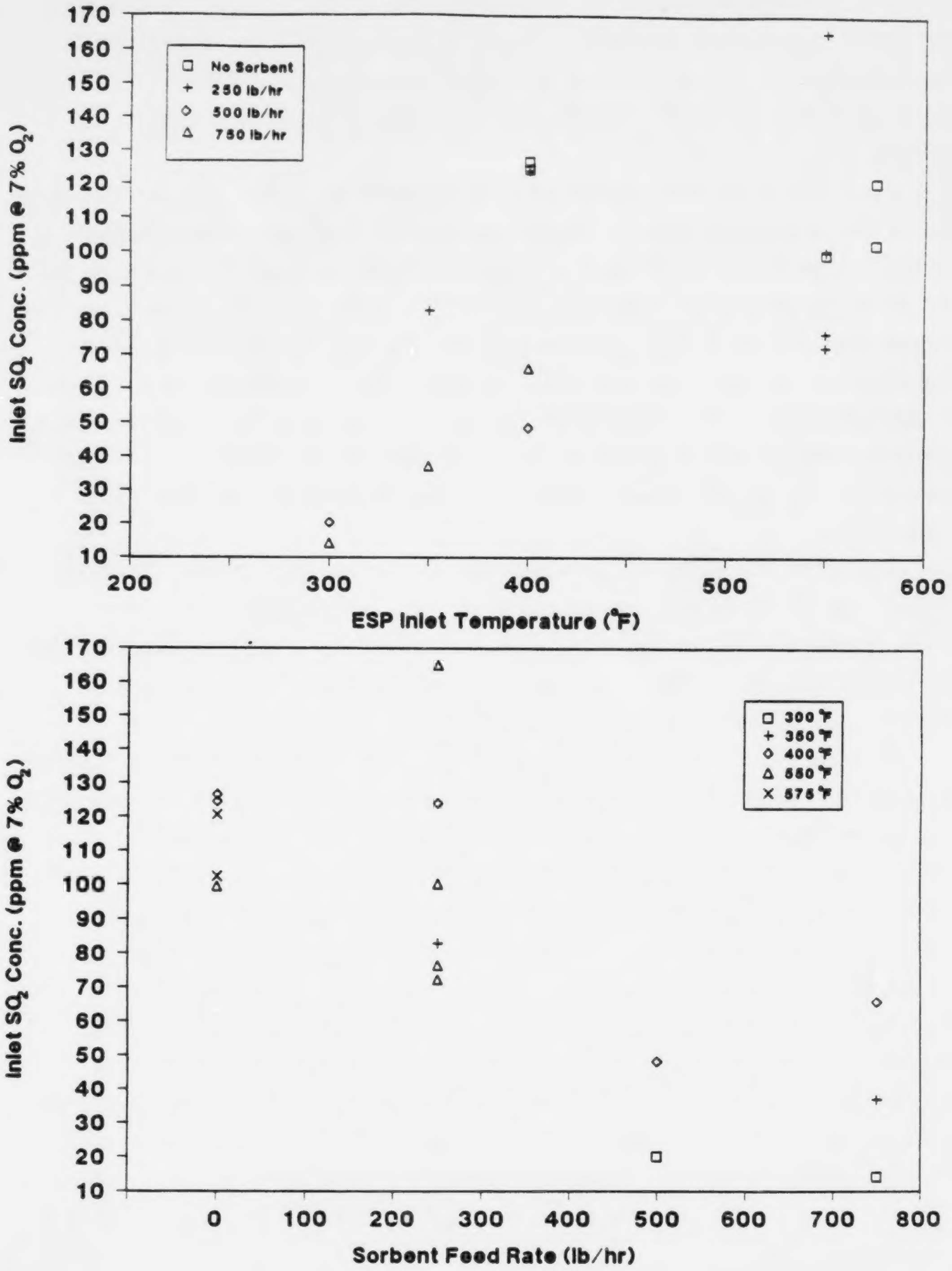


**Figure 3-1. Inlet $SO_2$ concentration as a function of ESP inlet temperature and sorbent feed rate for the FSI system at Dayton.**

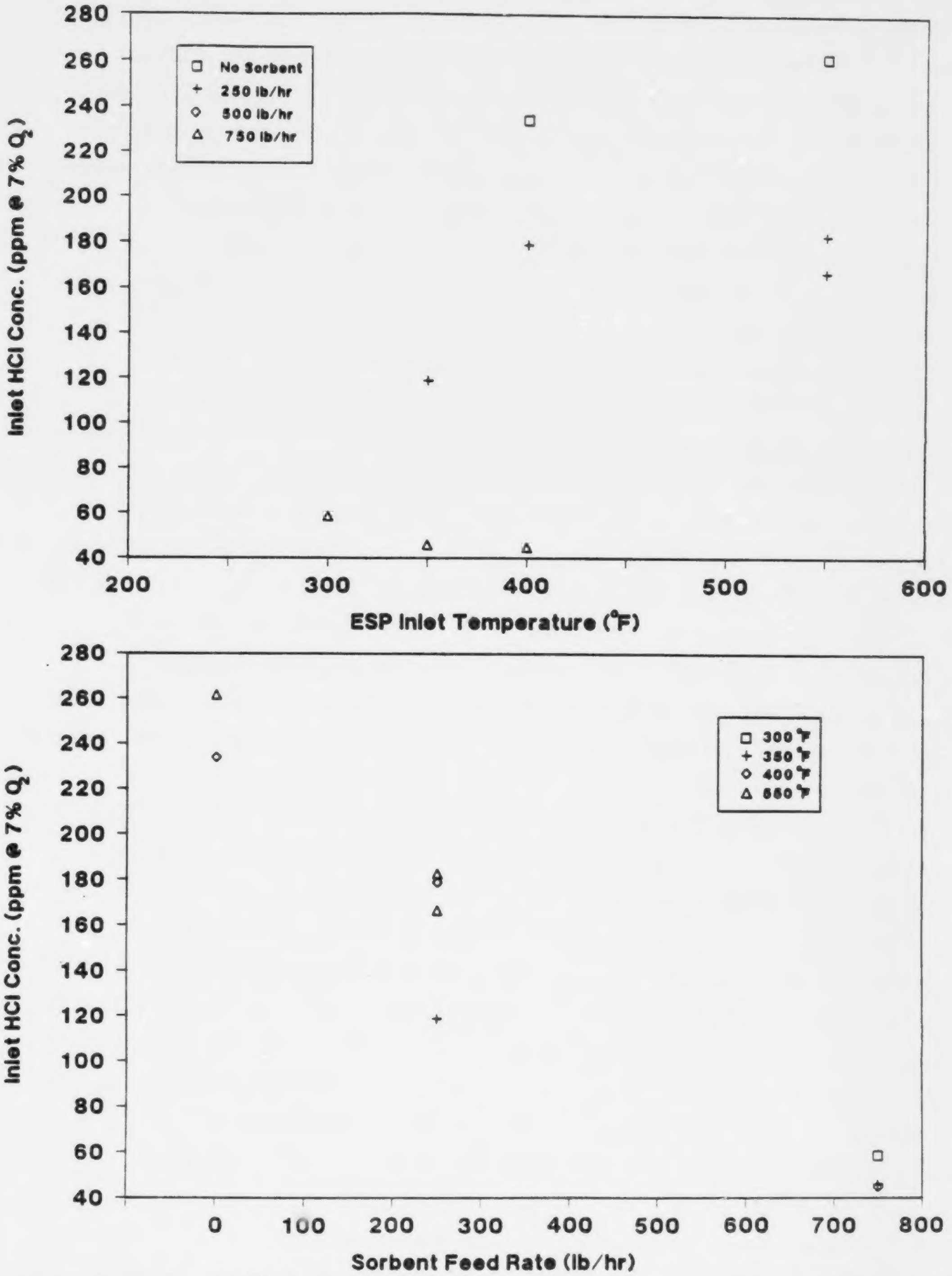


**Figure 3-2. Inlet HCl concentration as a function of ESP inlet temperature and sorbent feed rate for the FSI system at Dayton.**

Simultaneous measurements of $SO_2$ at the ESP inlet and outlet during parametric testing at 300 and 400°F indicate no additional $SO_2$ removal occurred across the ESP with furnace sorbent injection. At the ESP inlet, $SO_2$ concentrations averaged 48 and 20 ppm for the two parametric test conditions. At the ESP outlet, the corresponding $SO_2$ concentrations were 57 and 21 ppm. During the screening tests conducted at an ESP inlet temperature of 550°F (conditions 5, 6, and 7) averaged 54 ppm, or roughly 35 percent lower than the average $SO_2$ levels at the ESP inlet of 83 ppm.

In Table 3-5, particulate data from the parametric test with FSI at Dayton are presented. Six test runs were conducted. Although the temperatures and SCA's differed significantly between the two test conditions, no difference in performance is observed. At flue gas flows of about 85,000 acfm and 70,000 acfm, SCA's of 383 and 466 $ft^2$/1,000 acfm, respectively, PM removal efficiencies and outlet emissions were very similar. Outlet PM concentrations ranged from 0.017 to 0.024 gr/dscf over three runs and averaged 0.021 gr/dscf for Runs 10 to 12 conducted at an ESP inlet of 400°F temperature. For Runs 13 to 15 conducted an ESP inlet temperature of 300°F, outlet PM concentrations ranged from 0.0068 to 0.030 gr/dscf and averaged 0.022 gr/dscf. Under both sets of conditions, average ESP removal efficiency was 98 percent. There was no apparent effect of inlet PM on performance.

Particulate data from Dayton without furnace sorbent injection are presented in Section 2.2.1. Outlet PM concentrations without sorbent injection ranged from 0.0063 to 0.023 gr/dscf over the course of nine test runs, averaging 0.011 gr/dscf. With average inlet PM concentrations approximately twice as high during the tests with FSI, 1.13 gr/dscf with FSI and 0.63 gr/dscf without sorbent, the outlet PM concentrations were also approximately twice as high, averaging 0.022 gr/dscf. The PM removal efficiency of the ESP during tests with and without FSI are roughly equal.

Metals data for six parametric test runs are presented in Table 3-6. Removal efficiencies for arsenic, cadmium, lead, and chromium were consistently at 96, 94, 93, and 84 percent, respectively, and did not depend on the ESP inlet temperature. These removal efficiencies are 2 to 14 percent lower than the corresponding PM removal efficiency. Removal

TABLE 3-5. PARTICULATE DATA FOR DAYTON WITH FURNACE SORBENT INJECTION

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | PM Removal Efficiency (percent) |
|---|---|---|---|---|---|---|
| Combustor = Normal | 10 | 397 | 86,500 | 0.72 | 0.024 | 96.7 |
| FSI = 500 lb/hr | 11 | 391 | 82,900 | 1.37 | 0.021 | 98.5 |
| ESP = 400°F inlet | 12 | 395 | 86,400 | 1.49 | 0.017 | 98.9 |
| Average | | 394 | 85,300 | 1.19 | 0.021 | 98.0 |
| Combustor = Normal | 13 | 297 | 72,700 | 1.06 | 0.030 | 97.2 |
| FSI = 500 lb/hr | 14 | 301 | 70,600 | 1.07 | 0.028 | 97.4 |
| ESP = 300°F inlet | 15 | 296 | 66,900 | 1.25 | 0.0068 | 99.5 |
| Average | | 298 | 70,100 | 1.13 | 0.022 | 98.0 |

TABLE 3-6. METALS DATA FOR DAYTON WITH FURNACE SORBENT INJECTION

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Inlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Removal Efficiency (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal | 10 | 397 | 0.024 | 196 | 1,110 | 217 | 34,587 | 708 | 125 | 6.84 | 77.6 | 8.7 | 1,786 | 567 | 8.58 | 95.8 | 91.5 | 95.1 | 93.7 | 2.8 | 91.7 |
| FSI = 500 lb/hr | 11 | 391 | 0.021 | 184 | 1,189 | 40 | 21,872 | 1,270 | 81 | 3.97 | 56.2 | 6.7 | 1,350 | 909 | 9.05 | 97.6 | 94.6 | 81.3 | 93.0 | 18.8 | 87.4 |
| ESP = 400°F inlet | 12 | 395 | 0.017 | 365 | 1,158 | 41 | 24,358 | 940 | 100 | 6.25 | 34.3 | 10.6 | 1,644 | 795 | 8.54 | 98.3 | 97.0 | 74.5 | 93.3 | 15.3 | 91.5 |
| Average | | 394 | 0.021 | 248 | 1,152 | 99 | 26,939 | 973 | 102 | 5.69 | 56.0 | 8.6 | 1,593 | 757 | 8.72 | 97.2 | 94.4 | 83.6 | 93.3 | 12.8 | 90.2 |
| Combustor = Normal | 13 | 297 | 0.030 | 249 | 880 | 47 | 18,550 | 939 | 59 | 10.7 | 79.2 | 13.1 | 2,180 | 602 | 9.67 | 95.1 | 89.8 | 68.8 | 86.7 | 27.7 | 81.6 |
| FSI = 500 lb/hr | 14 | 301 | 0.028 | 91 | 1,385 | 138 | 40,006 | 735 | 41 | 6.64 | 76.1 | 10.3 | 2,111 | 521 | 8.69 | 92.7 | 94.5 | 92.5 | 94.7 | 29.1 | 78.8 |
| ESP = 300°F inlet | 15 | 296 | 0.0068 | 72 | 1,005 | 50 | 22,086 | 1,046 | 49 | ND | 9.5 | 5.0 | 230 | 1,005 | 13.1 | 100 | 99.1 | 90.3 | 99.0 | 6.9 | 74.0 |
| Average | | 298 | 0.022 | 137 | 1,090 | 78 | 26,881 | 907 | 49 | 5.78 | 54.9 | 9.4 | 1,507 | 709 | 10.5 | 96.0 | 94.5 | 83.9 | 93.5 | 21.3 | 78.1 |

efficiency for nickel averaged 90 percent for one test condition (400°F) and 78 percent for the other test condition (300°F). However, this difference is probably due to the normal variation in ESP performance for nickel rather than changes in temperature and SCA. The removal efficiencies for arsenic, cadmium, lead, chromium, and nickel with FSI were 2, 4, 5, 10, and up to 16 percent lower, than the corresponding metals removal efficiencies measured without sorbent injection. Thus, use of FSI may result in lower ESP performance for arsenic, cadmium, lead, chromium, and nickel relative to performance with no sorbent injection. Mercury removal efficiencies averaged 12 percent for three runs at 400°F and 21 percent for three runs at 300°F. This difference may be due to temperature, but may also reflect variability in sampling accuracy between runs. No mercury removal was observed for the tests conducted at 400° and 550°F without sorbent injection. Thus use of FSI may increase mercury removal compared to operations without sorbent injection, but the removal of mercury will be small.

CDD/CDF data from the parametric testing are presented in Table 3-7. At an ESP inlet temperature of 400°F, outlet CDD/CDF concentrations were between 1,018 and 1,990 ng/dscm at 7 percent $O_2$ and averaged 1,480 ng/dscm for the runs. The inlet CDD/CDF concentrations ranged from 22.3 to 49.1 ng/dscm and averaged 38.2 ng/dscm. At an ESP inlet temperature of 300°F, outlet CDD/CDF concentrations ranged from 352 to 1,030 ng/dscm and averaged 659 ng/dscm for the runs. The inlet CDD/CDF concentrations ranged from 7.4 to 23.6 ng/dscm and averaged 13.9 ng/dscm.

Both test conditions with limestone injected into the furnace showed an increase in CDD/CDF concentrations across the ESP despite low ESP inlet temperatures. At the ESP inlet, CDD/CDF concentrations were at most 46 ng/dscm. Due to significant amounts of PM assumed to be removed in the quench spray chamber, these low concentrations may indicate that much of the CDD/CDF associated with PM was removed in the quench spray chamber. The CDD/CDF concentrations at the mixing chamber for the 300 and 400°F tests were 1,070 and 2,450 ng/dscm at 7 percent $O_2$. At the ESP outlet, all CDD/CDF concentrations were at least 352 ng/dscm. These data indicate that the level of CDD/CDF concentration at the ESP outlet depends on temperature.

TABLE 3-7. CDD/CDF DATA FOR DAYTON WITH FURNACE SORBENT INJECTION

| Test Conditions | Run Number | ESP Inlet Temperature (°F) | Mixing Chamber CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal | 10 | 397 | NM[a] | 49.1 | 1,990 | - 3,950 |
| FSI = 500 lb/hr | 11 | 391 | NM | 22.3 | 1,434 | - 6,330 |
| ESP = 400°F inlet | 12 | 395 | 2,450 | 43.0 | 1,018 | - 2,267 |
| Average | | 394 | 2,450 | 38.2 | 1,480 | - 4,180 |
| Combustor = Normal | 13 | 297 | NM | 8.4 | 1,030 | -13,800 |
| FSI = 500 lb/hr | 14 | 301 | 1,240 | 23.6 | 596 | - 2,425 |
| ESP = 300°F inlet | 15 | 296 | 910 | 10.6 | 352 | - 3,221 |
| Average | | 298 | 1,070 | 13.9 | 659 | - 6,490 |

[a] NM = not measured.

At 400°F an average of 1,550 ng/dscm of CDD/CDF was emitted from the ESP. At 300°F, an average of 659 ng/dscm was emitted from the ESP.

In comparison, data collected at Dayton without sorbent injection at 400°F showed ESP outlet CDD/CDF emissions of about 865 ng/dscm (Section 2.2.1.4). This suggests that the use of a FSI/ESP system at Dayton did not lower CDD/CDF emissions.

## 3.3 SUMMARY OF PERFORMANCE

Performance of individual units with furnace sorbent injection followed by an ESP was discussed in Section 3.2. The data are evaluated as a whole in this section. Section 3.3.1 evaluates acid gas performance, Section 3.3.2 evaluates particulate performance, Section 3.3.3 evaluates metals performance, and Section 3.3.4 evaluates CDD/CDF performance.

### 3.3.1 Acid Gas

As discussed in Section 3.1, $SO_2$ readily reacts with lime at typical furnace temperatures (1400 to 1800°F). The removal of $SO_2$ depends on the amount of lime calcined from limestone and the mixing of the lime and flue gases in the furnace. HCl is not reactive with lime at typical furnace temperatures, but is removed at lower temperatures downstream of the furnace. These differing reaction temperatures can lead to preferential removal of $SO_2$ over HCl in systems operating at below or only slightly above stoichiometric sorbent feed rates.

Of the operating parameters that influence FSI acid gas control performance, stoichiometric ratio appears to be the most significant. As demonstrated at Dayton, increasing the limestone feed rate (stoichiometric ratio) decreased $SO_2$ and HCl emissions. A secondary factor affecting $SO_2$ emissions is the flue gas temperature at the ESP inlet. At flue gas temperatures of less than 400°F with sufficient limestone injection, $SO_2$ emissions at Dayton decreased as the flue gas temperature was lowered. There may be an effect of ESP inlet temperature on HCl emissions, but the data are inconclusive because of water scrubbing of HCl during flue gas cooling. Combustors using heat recovery to cool flue gas may not perform similarly. Finally, based on the Dayton data, it appears that most of the $SO_2$ and HCl removal occurs prior to the ESP inlet and that little removal occurs across the ESP.

At 300°F at Dayton, $SO_2$ and HCl emissions averaged 21 and 35 ppm at 7 percent $O_2$, respectively. However, high limestone injection rates (estimated stoichiometric ratios of 1.6-5) were used during these tests. Testing conducted at the Alexandria MWC at an ESP inlet temperature of 360°F and a lower lime feed rate yielded average outlet $SO_2$ and HCl concentrations of 37 and 166 ppm, respectively.

These data indicate use of furnace sorbent injection of lime or limestone can reduce both $SO_2$ and HCl emissions by 50 percent or more. Higher levels of removal can be achieved by increasing sorbent stoichiometric ratio and reducing flue gas temperatures to less than 400°F.

### 3.3.2 Particulate Matter

Both of the FSI/ESP systems evaluated yielded outlet PM emissions averaging about 0.025 gr/dscf. However, both systems were only designed to achieve 0.03 gr/dscf or lower. As shown at Dayton, use of FSI can increase both inlet and outlet PM emissions over operation without FSI at the same facility. However, Alexandria showed no increase in outlet PM emissions with FSI as compared to emissions without FSI.

Outlet PM emissions of less than 0.03 gr/dscf at 12 percent $CO_2$ can be achieved by FSI/ESP systems applied to existing MWC's. At new MWC's, a level of 0.01 gr/dscf at 12 percent is attainable, based on analyses with SD/ESP (see Section 6.0) systems. As discussed in Section 2, however, more ESP fields may be required to meet this level.

### 3.3.3 Metals

In general, metals removal by FSI/ESP systems, as demonstrated at Dayton, appears to be consistent with PM removal. The measured PM removal efficiency at Dayton with FSI was 98 percent. Removal of arsenic, cadmium, and lead was consistently higher than 93 percent. Chromium removal was 84 percent. Nickel removal was erratic, with average removal efficiencies of 78 and 90 percent at 300 and 400°F, respectively. Removal efficiencies for all these metals would be expected to increase with more effective PM removal. Although every run yielded lower outlet than inlet mercury concentrations, mercury removal efficiencies were less than 30 percent for all runs.

With an FSI/ESP system able to achieve outlet PM emissions of 0.03 gr/dscf, arsenic, cadmium, and lead can be removed at greater than 90 percent efficiency. Roughly 80 percent removal efficiency of chromium and nickel can be achieved. Limited reductions in mercury (up to 20 percent) may also be achievable.

### 3.3.4 CDD/CDF

The available data show wide variations in CDD/CDF removal performance. Outlet CDD/CDF emissions above 1,000 ng/dscm and below 60 ng/dscm have been measured at two separate MWC facilities with FSI/ESP systems. At Dayton, a mass burn refractory combustor using a relatively high limestone feed rate, average CDD/CDF emissions of 659 ng/dscm at an ESP inlet temperature of 300°F and 1,550 ng/dscm at 400°F were measured at the ESP outlet. Tests conducted at Dayton with and without FSI at an ESP inlet temperature of 400°F showed similar emission levels of CDD/CDF. At Alexandria, a mass burn waterwall combustor using a low lime feed rate and an ESP inlet temperature of 360°F, low outlet CDD/CDF concentrations were measured (<60 ng/dscm) which are similar to CDD/CDF emissions measured at two other combustors of the same design. There are insufficient data to determine if the use of lime rather than limestone affects performance. Based on the similarity in outlet concentrations of CDD/CDF with and without FSI at similar operating conditions, FSI does not significantly reduce CDD/CDF emissions from an ESP.

## 3.4 REFERENCES

1. Albertson, D.M. and M. L. Murphy. (Energy Products of Idaho). City of Tacoma Steam Plant No. 2 Pilot Plant Testing and Ash Analysis Program. Prepared for City of Tacoma, Department of Public Utilities. Tacoma, Washington. December 1987.

2. Zurlinden, R.A., A. Winkler, and J.L. Hahn (Ogden Projects, Inc._ Environmental Test Report, Alexandria/Arlington Resources Recovery Facility, Units 1, 2, and 3. Prepared for Ogden Martin Systems of Alexamdria/Arlington, Inc. Alexandria, Virginia. Report No. 144B. March 9, 1988.

3. Zurlinden, R.A., H.P. Von Dem Fange, and J.L. Hahn (Ogden Projects, Inc.). Environmental Test Report, Alexandria/Arlington Resource Recovery Facility, Units 1, 2, and 3. Prepared for Ogden Martin Systems of Alexandria/Arlington, Inc. Alexandria, Virginia. Report No. 144A (Revised). January 8, 1988.

4. Radian Corporation. Preliminary Data from October-November 1988 Testing at the Montgomery County South Plant, Dayton, Ohio.

# 4.0 DUCT SORBENT INJECTION FOLLOWED BY AN ELECTROSTATIC PRECIPITATOR

Section 4 describes the technology and performance of duct sorbent injection (DSI) systems with an ESP for PM control. In Section 4.1, DSI/ESP operation and design is described. Section 4.2 presents descriptions of MWC's equipped with DSI/ESP systems for which emissions data are available and summarizes the available data. In Section 4.3, the performance of DSI/ESP systems relative to the control of $SO_2$, HCl, PM, metals, and CDD/CDF emissions is discussed.

## 4.1 PROCESS DESCRIPTION

Duct sorbent injection is designed to control acid gas emissions. Powdered sorbent, usually hydrated lime [$Ca(OH)_2$], is injected into the flue gas upstream of the particulate control device. The sorbent is generally injected through a venturi or into a reactor vessel just upstream of the ESP. The residence time prior to the ESP is generally one to two seconds. The sorbent reacts rapidly with the acid gases to form salts which, in addition to the flyash and unreacted sorbent, are removed by the ESP. Lower system operating temperatures increase sorbent reactivity and increase removal of acid gases as well as condensible metals and organics. At the injection point, the flue gas temperature can range from less than $300^oF$ to roughly $600^oF$. Flue gas can be cooled upstream of the injection point by heat exchange, such as by an economizer or air-to-air heat exchanger, humidification, or addition of lower temperature air.

The operation and design of ESP's following DSI is similar to the operation of an ESP without sorbent injection. The increased particulate loading and changed particulate characteristics due to the injected sorbent are not expected to significantly decrease PM removal efficiency by an ESP. However, larger ESP specific collection areas (SCA's) may be needed to achieve the same outlet PM emissions as systems without sorbent injection. Design of ESP's is described in Section 2.1.

## 4.2 SUMMARY OF TEST DATA

Section 4.2 presents the available emissions data for MWC facilities with DSI/ESP systems. The only data available are for the Dayton MWC. A description of this facility and a summary and analysis of the emission data are provided.

The effects of stoichiometric ratio, ESP inlet temperature, and inlet acid gas concentration on acid gas removal are discussed in this section. The effect of SCA on ESP performance for particulate removal is also discussed. Finally, this section discusses the effects of inlet CDD/CDF concentration and ESP inlet temperature on CDD/CDF removal.

### 4.2.1 Dayton[1]

The Montgomery County South Incinerator plant in Dayton, Ohio, includes three nearly identical Volund refractory-lined combustors. PM emissions are controlled by ESP's. A complete description of the facility is provided in Section 2.2.1.4.

In November and December 1988, testing was conducted by EPA on Unit 3. Tests were conducted with furnace sorbent injection, duct sorbent injection, and without sorbent injection. A complete description of the test program is presented in Section 2.2.1.4. Results from the duct sorbent injection tests are reported here. Hydrated lime was injected into a vertical duct prior to the ESP at a temperature of 350 to 400°F. The results from tests without sorbent are presented in Section 2.2.1.4. The results from tests with furnace sorbent injection are reported in Section 3.2.

The acid gas data are presented in Table 4-1. Sixteen test runs were conducted at ESP inlet temperatures of 300, 350, and 400°F and sorbent injection rates of 160, 320, and 480 lbs/hr. Runs 11 through 14 were conducted in November as part of the test screening phase. Runs 16, 17, and 18 were conducted in December as part of the more detailed parametric testing phase. Because the duct injector system was installed primarily to protect the ESP from acid gas corrosion during the testing and was not designed to achieve maximum sorbent utilization, the acid gas performance data collected during the tests may not be indicative of performance levels achievable by commercial DSI systems and should be used only to show trends in performance. The relatively low acid gas concentrations at the ESP inlet compared to other MWC's may be due to acid gas scrubbing by the water quench chamber located ahead of the ESP inlet sampling point.

## TABLE 4-1. ACID GAS DATA FOR DAYTON WITH DSI

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Stoichiometric Ratio[a] | Acid Gas Concentration (ppmv, dry at 7% $O_2$) | | | | Acid Gas Removal Efficiency (%) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Inlet | | Outlet | | | |
| | | | | $SO_2$[b] | HCl[b] | $SO_2$ | HCl | $SO_2$ | HCl |
| Combustor = Normal | 11A | 400 | NM[c] | NM | 141 | NM | 29.7 | -- | 78.9 |
| DSI = 160 lb/hr | 11B | 400 | 4.9 | 106 | 204 | 52.9 | 37.9 | 50.1 | 81.4 |
| ESP = 400°F inlet | 11C | 400 | 4.7 | 123 | 217 | 56.7 | 35.6 | 53.9 | 83.6 |
| Average | | 400 | 4.8 | 114 | 187 | 54.8 | 34.4 | 52.0 | 81.3 |
| Combustor = Normal | 12A | 400 | 13 | 115 | 142 | 32.2 | 16.3 | 72.0 | 88.5 |
| DSI = 480 lb/hr | 12B | 400 | 11 | 141 | 211 | 34.8 | 32.2 | 75.3 | 84.7 |
| ESP = 400°F inlet | 12C | 400 | 10 | 130 | 191 | 36.8 | 19.7 | 71.7 | 89.7 |
| Average | | 400 | 11 | 129 | 181 | 34.6 | 22.8 | 73.0 | 87.6 |
| Combustor = Normal | 13A | 350 | 4.5 | 108 | 159 | 65.6 | 50.8 | 39.3 | 68.1 |
| DSI = 160 lb/hr | 13B | 350 | 4.6 | 117 | 177 | 56.9 | 34.9 | 51.4 | 80.3 |
| ESP = 350°F inlet | 13C | 350 | 6.6 | 138 | 263 | 54.6 | 34.9 | 60.4 | 86.7 |
| Average | | 350 | 5.2 | 121 | 200 | 59.0 | 40.2 | 50.4 | 78.4 |
| Combustor = Normal<br>DSI = 480 lb/hr<br>ESP = 350°F inlet | 13D | 350 | 15 | 111 | 126 | 35.7 | 17.4 | 67.8 | 86.2 |
| Combustor = Normal | 16 | 306 | 9.0[d] | 93 | 119 | 30.0 | 12.0 | 67.9 | 89.9 |
| DSI = 320 lb/hr | 17 | 305 | 9.6[d] | 122 | 128 | 46.8 | 6.8 | 61.5 | 94.7 |
| ESP = 300°F inlet | 18 | 306 | 7.0[d] | 139 | 86 | 40.0 | 8.0 | 71.2 | 90.7 |
| Average | | 306 | 8.5 | 119 | 111 | 38.9 | 8.9 | 66.9 | 91.8 |
| Combustor = Normal | 14A | 300 | 30 | 67 | 93 | 38.3 | 11.7 | 42.8 | 87.4 |
| DSI = 480 lb/hr | 14B | 300 | 28 | 74 | 90 | 43.6 | 13.0 | 41.2 | 85.6 |
| ESP = 300°F inlet | 14C | 300 | 28 | 76 | 99 | 45.2 | 10.9 | 40.3 | 89.0 |
| Average | | 300 | 29 | 72 | 94 | 42.3 | 11.9 | 41.5 | 87.3 |

[a] Calculated based on measured HCl and $SO_2$ concentrations at the ESP inlet.

[b] Acid gas concentrations at ESP inlet may reflect partial scrubbing of $SO_2$ and HC1 by water sprays in quench chamber located between the combustor and ESP inlet.

[c] NM = Not measured.

[d] Hydrated lime feed rate = 250 lb/hr.

During screening test Runs 11A, 11B, 11C, 13A, 13B, and 13C, the sorbent feed rate was 160 lbs/hr. The ESP inlet temperature during these runs was set at 400°F for Runs 11A, B, and C and at 350°F for Runs 13A, B, and C. $SO_2$ concentrations at the ESP outlet during the runs conducted at 400°F ranged from 53 to 57 ppm at 7 percent $O_2$ and averaged 55 ppm while the runs conducted at 350°F ranged from 55 to 66 ppm and averaged 59 ppm. Average $SO_2$ removal efficiencies across the ESP at both temperatures were relatively consistent at roughly 50 percent. Outlet HCl concentrations during the runs at 400°F ranged from 30 to 38 ppm and averaged 34 ppm while the runs at 350°F ranged from 35 to 51 ppm and averaged 40 ppm. Across the ESP, HCl removal efficiencies at both temperatures were also consistent at roughly 80 percent.

During screening test Runs 12A, 12B, 12C, 13D, 14A, 14B, and 14C, the sorbent feed rate was 480 lbs/hr. The ESP inlet temperature during these runs was set at 400°F for Runs 12A, B, and C; 350°F for Run 13D; and 300°F for Runs 14A, B, and C. $SO_2$ concentrations at the ESP outlet during the runs conducted at 400°F ranged from 32 to 37 ppm and averaged 35 ppm. Outlet $SO_2$ concentrations during the single run conducted at 350°F was 36 ppm and during the three runs conducted at 300°F ranged from 38 to 45 ppm and averaged 42 ppm. $SO_2$ removal efficiencies across the ESP were relatively consistent at both 400°F and 350°F, ranging from 68 to 75 percent and averaging 70 percent. At 300°F, the $SO_2$ removal efficiency across the ESP ranged from 40 to 43 percent and averaged 41 percent. In addition to the somewhat higher outlet $SO_2$ concentration during the runs at 300°F, the reduced $SO_2$ removal efficiency at 300°F also reflects a lower inlet $SO_2$ level of 67 to 76 ppm versus inlet concentrations of 111 to 141 ppm during the 350 and 400°F runs. The reduced inlet $SO_2$ concentration and lower removal efficiency at 300°F may have been partially due to problems with clumping of hydrated lime around the sorbent injector nozzles and plugging of the sorbent feed system at these lower temperatures. Outlet HCl concentrations during the runs at 400°F ranged from 16 to 32 ppm and averaged 23 ppm and was 17 ppm during the single run at 350°F. Outlet HCl concentrations during the runs at 300°F ranged from 11 to 13 ppm and averaged 12 ppm. HCl removal efficiencies across the ESP during all of these runs were relatively consistent at all of the temperatures, ranging from 85 to 90 percent and averaging 87 percent.

During parametric test Runs 16, 17, and 18, the ESP inlet temperature was set at 300°F although the actual averages during each run were slightly higher. The sorbent feed rate was 320 lbs/hr during Run 16, but was reduced to 250 lbs/hr during Runs 17 and 18 due to the sorbent clumping and injector plugging problems mentioned above. $SO_2$ concentrations at the ESP outlet were 30 ppm during Run 16, and 47 and 40 ppm during Runs 17 and 18. Average $SO_2$ removal efficiencies across the ESP during all three runs ranged from 62 to 71 percent and did not show any clear differences as a function of lime feed rates. Outlet HCl concentrations were 12 ppm during Run 16, 7 ppm during Run 17, and 8 ppm during Run 18. Average HCl removal efficiencies across the ESP during all three runs ranged from 90 to 95 percent and did not show any clear differences as a function of lime feed rates.

Taken in aggregate, the Dayton data indicate that increasing the sorbent feed rate will reduce outlet acid gas concentrations. However, over the range of temperatures examined, ESP operating temperature had relatively little effect on outlet acid gas emissions or removal efficiency.

Overall $SO_2$ and HCl removal efficiencies are shown in Figures 4-1 and 4-2, respectively, as a function of stoichiometric ratio. Both $SO_2$ and HCl removal efficiency generally increase as the stoichiometric ratio increases. The lower $SO_2$ removal efficiencies measured at high stoichiometric feed rates during Runs 14A, B, and C (not shown on either figure) are a result of unusually low inlet $SO_2$ concentrations and possible sorbent injector problems encountered at low temperatures, high lime feed rates, and high flue gas humidity. The outlet $SO_2$ concentrations measured during these runs are similar to those measured during the other tests with stoichiometric ratios above 7. These data suggest that increasing the stoichiometric ratio above about 7 did not provide additional acid gas removal because of constraints on lime and flue gas mixing associated with the injection system used during the Dayton testing.

The removal efficiency and outlet emission data for $SO_2$ and HCl do not show any significant relationship with ESP inlet temperature. At the highest sorbent feed rate, outlet $SO_2$ emissions remain consistently near 35

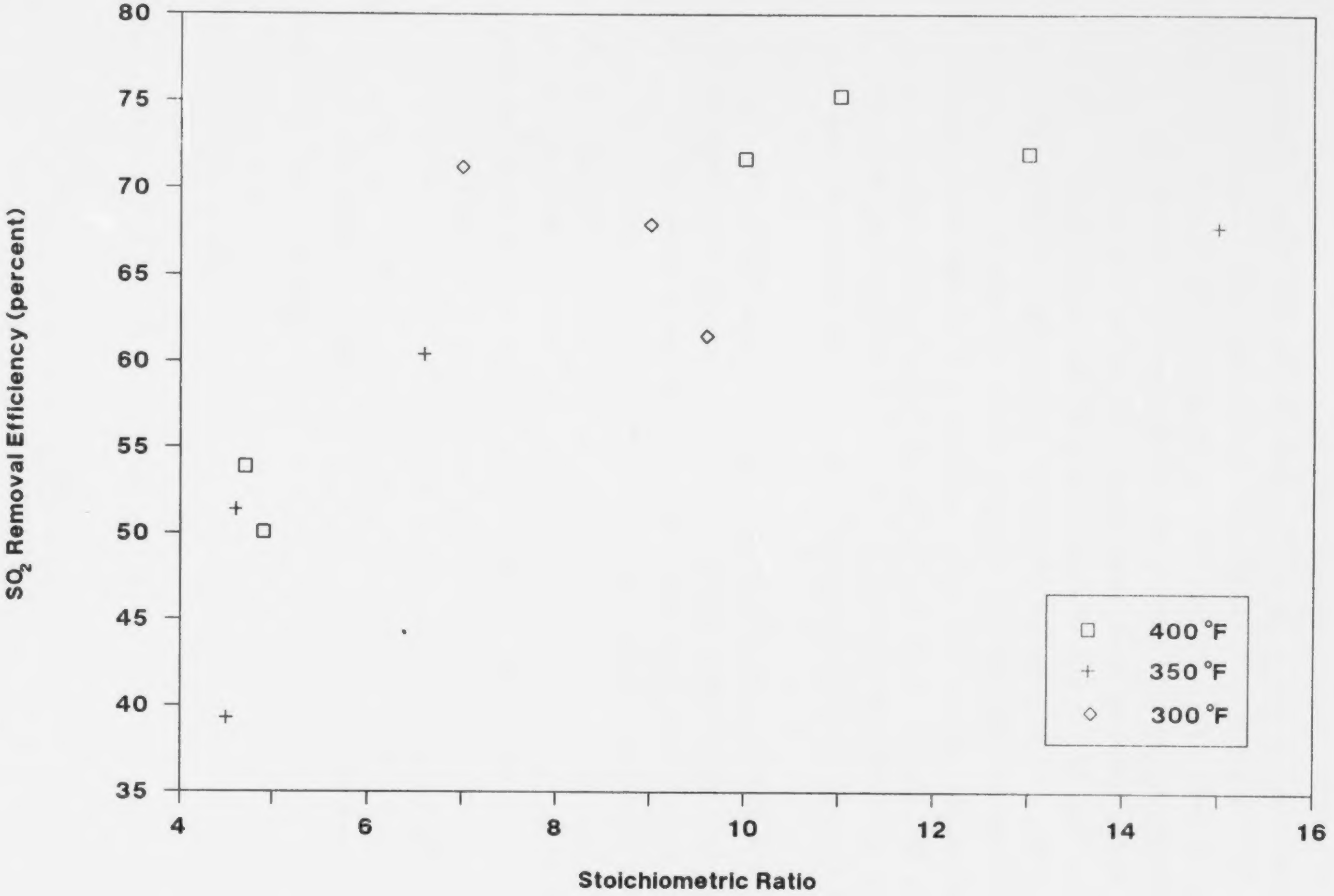


Figure 4-1. $SO_2$ removal efficiency as a function of stoichiometric ratio at the Dayton DSI/ESP system.

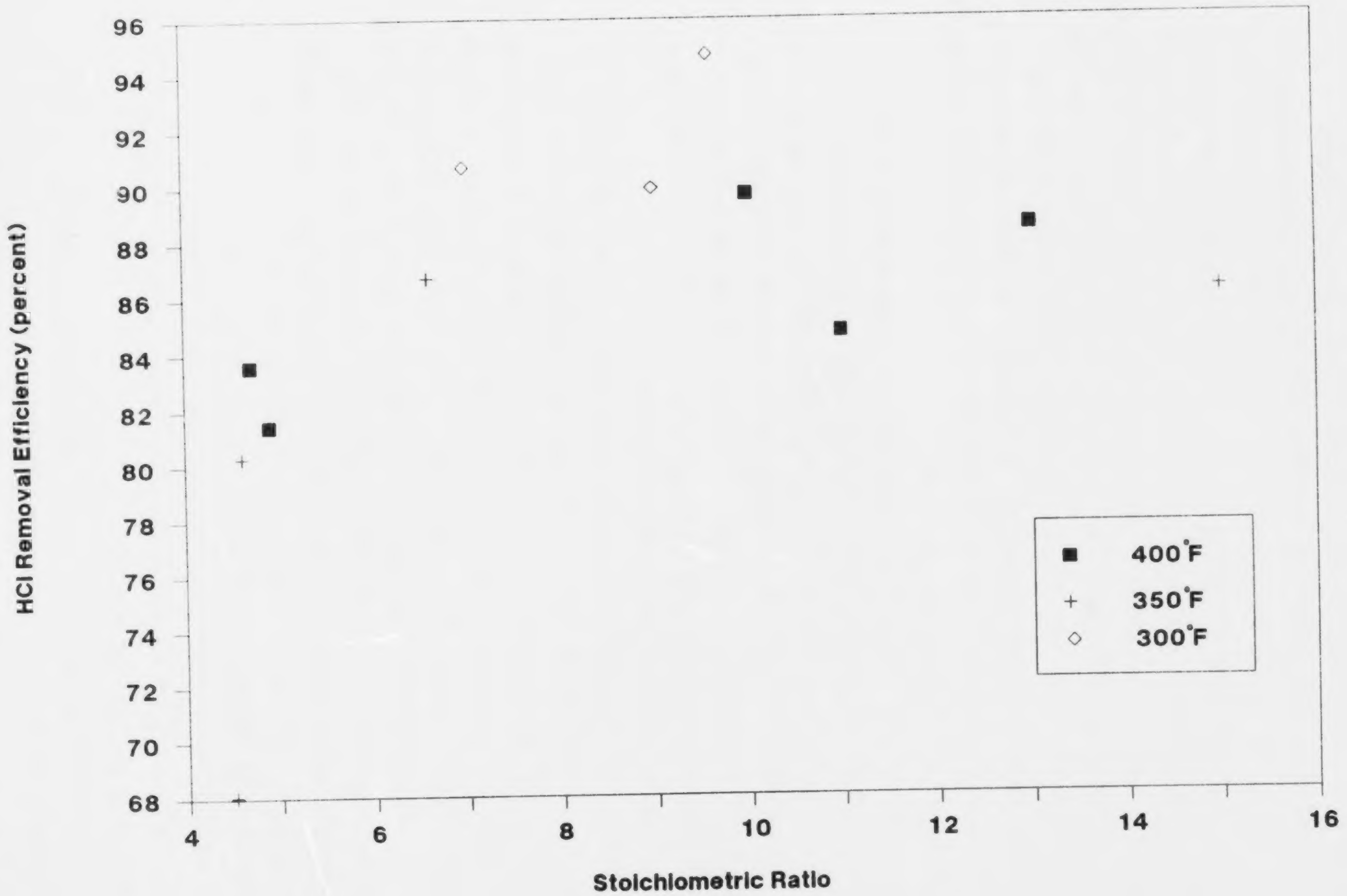


Figure 4-2. HCl removal efficiency as a function of stoichiometric ratio at the Dayton DSI/ESP system.

to 40 ppm for temperatures of 300 to 400°F. At these same feed rates, HCl emissions were between 10 and 20 ppm for all but one run. There is no apparent effect of inlet $SO_2$ and HCl concentrations on performance.

Particulate data are presented in Table 4-2 for the three parametric test runs. Outlet PM concentrations ranged from 0.0018 to 0.0039 gr/dscf at 12 percent $CO_2$ and averaged 0.0032 gr/dscf. The corresponding PM removal efficiencies were between 99.2 and 99.7 percent and averaged 99.4 percent. Although the flue gas flow rate was significantly higher for Run 16, giving a lower SCA, PM removal efficiency was highest during that run. The outlet PM emissions from the tests of DSI are similar to the results from tests with no sorbent injection, which demonstrated 0.0063 gr/dscf at 12 percent $CO_2$. The tests with furnace sorbent injection yielded much higher outlet PM emissions of about 0.020 gr/dscf.

Metals data for the three runs conducted are presented in Table 4-3. Average outlet metals concentrations were not detected for arsenic, 4 ug/dscm for chromium and nickel, 11 ug/dscm for cadmium, 360 ug/dscm for lead, and 490 ug/dscm for mercury. Removal efficiencies averaged greater than 98.9 percent for arsenic, cadmium, and lead. Chromium and nickel removal efficiencies were 97.8 and 96.7 percent, respectively. The removal efficiency for mercury was measured at 25 percent.

CDD/CDF data, which were collected simultaneously with the PM and metals data, are presented in Table 4-4. Outlet CDD/CDF concentrations ranged from 13.7 to 132 ng/dscm at 7 percent $O_2$ and averaged 57.2 ng/dscm. Increases in CDD/CDF concentrations were observed across the ESP, with the outlet concentrations being 2.6 to 380 times higher than those measured at the ESP inlet. Inlet CDD/CDF concentrations ranged from 0.31 to 8.4 ng/dscm and averaged 5.3 ng/dscm. The low inlet CDD/CDF concentrations may have been caused by the water spray quench chamber removing a significant amount of particulate as discussed in Section 3.2. At the mixing chamber, the CDD/CDF concentration during Run 16 was 5,350 ng/dscm. There are insufficient variations in ESP inlet temperature, inlet CDD/CDF concentration, and inlet PM to allow analyses of the effects of these parameters relative to CDD/CDF removal.

The outlet CDD/CDF emissions with DSI, 57 ng/dscm, are significantly lower than measured during tests with no sorbent addition in

TABLE 4-2. PARTICULATE DATA FOR DAYTON WITH DSI

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal<br>DSI = 320 lb/hr[a]<br>ESP = 300°F inlet | 16 | 306 | 83,700 | 0.604 | 0.0018 | 99.7 |
|  | 17 | 305 | 66,200 | 0.596 | 0.0039 | 99.4 |
|  | 18 | 306 | 63,200 | 0.481 | 0.0039 | 99.2 |
| Average |  | 306 | 71,000 | 0.560 | 0.0032 | 99.4 |

[a] Hydrated lime feed rate changed to 250 lb/hr for Runs 17 and 18.

TABLE 4-3. METALS DATA FOR DAYTON WITH DSI

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Inlet Concentration (µg/dscm at 7% $O_2$) | | | | | | Outlet Concentration (µg/dscm at 7% $O_2$) | | | | | | Removal Efficiency (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal | 16 | 306 | 0.0018 | 263 | 1,312 | 170 | 35,689 | 782 | 59 | ND[b] | 7.6 | 3.19 | 305 | 462 | ND | 100 | 99.4 | 97.9 | 99.0 | 34.4 | 100 |
| DSI = 320 lb/hr[a] | 17 | 305 | 0.0039 | 290 | 1,660 | 223 | 33,870 | 679 | 101 | ND | 13.3 | 4.09 | 375 | 490 | 5.3 | 100 | 99.1 | 98.0 | 98.8 | 22.8 | 94.4 |
| ESP = 300°F inlet | 18 | 306 | 0.0039 | 76 | 1,582 | 183 | 39,273 | 687 | 170 | ND | 11.5 | 4.20 | 403 | 522 | 6.7 | 100 | 99.2 | 97.5 | 98.9 | 17.7 | 95.7 |
| Average | | 306 | 0.0032 | 210 | 1,518 | 192 | 34,863 | 716 | 110 | ND | 10.8 | 3.83 | 361 | 491 | 4.0 | 100 | 99.2 | 97.8 | 98.9 | 25.0 | 96.7 |

[a] Hydrated lime feed rate for runs 17 and 18 was 250 lb/hr.

[b] ND = Not detected.

TABLE 4-4. CDD/CDF DATA FOR DAYTON WITH DUCT SORBENT INJECTION

| Test Conditions | Run Number | ESP Inlet Temperature (°F) | Mixing Chamber CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal | 16 | 306 | 5,350 | 7.17 | 26.0 | - 263 |
| DSI = 320 lb/hr[a] | 17 | 305 | NM[b] | 8.44 | 132 | -14,600 |
| ESP = 300°F inlet | 18 | 306 | NM | 0.31 | 13.7 | - 4,219 |
| Average | | 306 | 5,350 | 5.31 | 57.2 | - 6,360 |

[a] Hydrated lime feed rate for Runs 17 and 18 was 250 lb/hr.

[b] NM = Not measured.

Section 2.2.1.4, 866 to 17,100 ng/dscm and furnace sorbent injection in Section 3.2.2, 673 ng/dscm at an ESP inlet temperature of 300°F and 1,480 ng/dscm at an ESP inlet temperature of 400°F. At the same ESP inlet temperature, 300°F, CDD/CDF emissions with DSI were an order of magnitude lower than with FSI.

## 4.3 SUMMARY OF PERFORMANCE

Performance of the Dayton DSI/ESP system was evaluated in Section 4.2. Because the only available data are from Dayton, only the conclusions reached from the analyses of this single MWC are presented in this section. Section 4.3.1 evaluates acid gas performance. Section 4.3.2 presents the evaluations regarding PM performance. Section 4.3.3 presents the discussion for metals performance, and Section 4.3.4 summarizes CDD/CDF performance.

### 4.3.1 Acid Gas

At Dayton, with a non-commercial DSI/ESP system, outlet HCl emissions were shown to decrease with increasing stoichiometric ratio. HCl removal efficiencies of greater than 68 percent were demonstrated across the ESP during all test runs, and were between 85 and 95 percent during tests conducted at ESP inlet temperatures of 300 to 310°F. HCl concentrations at the ESP outlet during all tests were less than 60 ppm at 7 percent $O_2$. HCl removal efficiencies across the entire quench spray chamber and DSI/ESP system may have exceeded 90 percent. Based on these data, 80 percent HCl removal efficiency is achievable with DSI/ESP systems at temperatures of 400°F or less.

Removal efficiency for $SO_2$ and outlet $SO_2$ emissions at Dayton were relatively independent of temperature. Analysis of the effect of stoichiometric ratio showed that performance can be enhanced by increasing stoichiometric ratio. At ESP inlet temperatures of 300 to 400°F and 160 to 480 lb/hr of lime injection, $SO_2$ removal efficiencies averaged greater than 50 percent. At only one condition, ESP inlet temperature of 300°F, was an $SO_2$ removal efficiency of less than 50 percent obtained (42 percent). The inlet $SO_2$ concentrations were unusually low during this condition, and the outlet $SO_2$ emissions were similar to the results demonstrated at other test conditions. This suggests that lime and flue gas mixing constraints prevented the system from getting lower $SO_2$ emissions. Thus, at least 50 percent $SO_2$ removal efficiency is achievable by a DSI/ESP system.

### 4.3.2 Particulate Matter

At Dayton, with the DSI/ESP system, outlet PM emission were the same as measured without any sorbent injection. Thus, the outlet PM emissions of an existing ESP were not adversely affected when using DSI. Based on the analysis of ESP performance presented in Section 2.0, a DSI retrofit system can achieve outlet PM concentrations of 0.03 gr/dscf at 12 percent $CO_2$.

### 4.3.3 Metals

The metals removal efficiencies demonstrated at Dayton with the DSI/ESP system are the same as was measured at Dayton without sorbent injection. Therefore, removal efficiencies of greater than 90 percent for arsenic, cadmium, chromium, lead, and nickel are achievable with a DSI/ESP achieving 0.03 gr/dscf of PM. No mercury removal is expected to occur with a DSI/ESP system.

### 4.3.4 CDD/CDF

The average CDD/CDF emissions at Dayton with DSI/ESP and ESP inlet temperatures of $300^oF$ were 93 to 99.7 percent lower than measured without sorbent injection and ESP inlet temperatures of 400 to $575^oF$. This reduction cannot be attributed entirely to use of DSI, however, since emissions of CDD/CDF appear to be dependent on temperature. As shown during the Dayton tests without sorbent injection, CDD/CDF emissions at $400^oF$ were more than an order of magnitude lower than at $525^oF$ to $575^oF$. Therefore, higher CDD/CDF emissions will probably result with the DSI/ESP system at 350 to $450^oF$ than with the system operating at $300^oF$.

When compared to CDD/CDF emissions from the Dayton MWC with furnace sorbent injection at $300^oF$, the emissions with DSI are 90 percent lower. Assuming FSI does not affect outlet CDD/CDF emissions when compared to emissions without sorbent injection, (see Section 3.3.4), DSI can achieve a 90 percent decrease in CDD/CDF emissions when compared to emissions at the same temperature without duct sorbent injection.

## 4.4 REFERENCES

1. Radian Corporation. Preliminary Data for October - November 1988 testing at the Montgomery County South Plant, Dayton, Ohio.

## 5.0 DUCT SORBENT INJECTION FOLLOWED BY A FABRIC FILTER

Section 5 describes the technology and performance of duct sorbent injection (DSI) with a fabric filter for PM control. In Section 5.1, DSI/FF operation and design is described. Section 5.2 describes the MWC facilities equipped with DSI/FF systems with emissions data and summarizes the available data. In Section 5.3, performance of DSI/FF systems relative to the control of acid gas, PM, metals, and CDD/CDF emissions is described.

### 5.1 PROCESS DESCRIPTION

Duct sorbent injection technology with a fabric filter is very similar to duct sorbent injection with an ESP described in Section 4.1. However, because of the performance characteristics of a fabric filter, greater acid gas and organics removal is achievable than with an ESP.

Fabric filters remove particulate matter by passing flue gas through a porous barrier (filter bag). Filter bags are arranged vertically or horizontally into a number of defined compartments. Each compartment can operate independently of the other compartments. As the flue gas flows through the filter bags, particulate is collected on the filter surface, mainly through inertial impaction. The collected particulate builds up on the bag, forming a filter cake. The presence of unreacted sorbent in the collected particulate provides acid gas removal. Once excessive pressure drop across the filter cake is reached for the bags in a given compartment, that compartment is generally taken off-line, mechanically cleaned, and then placed back on-line.

Fabric filters are generally differentiated by cleaning mechanisms. Two main filter cleaning mechanisms are used: reverse-air and pulse-jet. In a reverse-air fabric filter, flue gas flows through unsupported filter bags, leaving the particulate on the inside of the bags. The bags are cleaned by blowing air through the filter in the opposite direction of the flue gas flow, causing the filter bag to collapse. The filter cake falls off and is collected in the hopper located below the filter bags. In a pulse-jet fabric filter, flue gas flows through supported filter bags, leaving particulate on the outside of the bags. Compressed air is introduced at the top of the bag, causing the bag to expand and the filter cake to fall off.

Fabric filters are capable of achieving very high particulate removal efficiencies. The PM control effectiveness of the fabric filter depends on flue gas and filter characteristics, including 1) the air-to-cloth ratio (expressed as acfm per square foot), and 2) the filter cleaning mechanism. The air-to-cloth ratio is optimized to give increased surface area without excess pressure drop. Collection efficiency increases as the air-to-cloth ratio decreases. Because pulse-jet fabric filters remove more filter cake than reverse-air units during the cleaning cycle, pulse-jet filters can be operated at higher air-to-cloth ratios with equal removal efficiencies.[1]

The increased particulate loading and changed particulate characteristics caused by DSI are not expected to significantly decrease the effectiveness of PM removal by a fabric filter. Larger surface area may be necessary, though, to ensure the same outlet PM emissions as achieved without sorbent injection.

## 5.2 SUMMARY OF TEST DATA

Section 5.2 presents the available emissions data for MWC's with DSI systems. A description of each facility and a summary and analysis of the emission data are provided for each facility.

The effects of stoichiometric ratio, fabric filter inlet temperature, and uncontrolled acid gas concentrations on acid gas removal are discussed in each section. The effects of air-to-cloth ratio on particulate removal is also discussed. The effects of inlet CDD/CDF concentration and fabric filter inlet temperature on CDD/CDF removal is discussed as well.

### 5.2.1 Claremont[2,3]

The SES Claremont facility in Claremont, New Hampshire, includes two identical Von Roll reciprocating grate combustor trains, each designed to combust 100 tons/day of MSW. Flue gas cooling is achieved by a boiler and economizer. Following heat recovery, the flue gas flows through a spark arrester where hot, glowing particles drop out. Located upstream of the spark arrester is an emergency water quench system to provide extra flue gas cooling if necessary. Additional flue gas cooling is accomplished through the addition of ambient air through an automatically adjustable damper located after the spark arrester. Downstream of the damper, dry hydrated lime is injected countercurrently into the flue gas in a venturi duct. The lime is fluidized with air in the feed duct. The typical lime feed rate is 190 to 220 lb/hr, with a maximum of 346 lb/hr. The design HCl removal efficiency is 90 percent.

Immediately following hydrated lime injection, flue gas enters a Wheelabrator fabric filter at a design flow of 25,000 acfm at 450°F. The fabric filter has three compartments, each with 225 woven fiberglass bags with an acid-resistant finish. The bags are cleaned with a pulse-jet system in which the bags are kept on-line while cleaned. Flue gas exiting the fabric filter is exhausted through separate 150-foot high stacks.

Compliance testing was conducted at the facility in May and July 1987. During the May test, flue gas was sampled at the FF outlet and analyzed for PM, $SO_2$, HCl, and $NO_x$. Additional simultaneous samples were taken from a single point at the FF inlet and analyzed for HCl. During the July test, flue gas at the FF outlet was analyzed for CDD/CDF. The combustor and DSI/FF system were operated under normal conditions during both test periods.

Acid gas data are presented in Table 5-1. Nine test runs were conducted at a FF inlet temperature of 450°F. Six of the test runs, three on each unit, were performed under a lime feed rate of approximately 190 lb/hr. The other three test runs were performed on Unit 1 at an elevated lime feed rate of 222 lb/hr. Outlet $SO_2$ concentrations at a lime feed rate of 190 lb/hr ranged from 38.1 to 337 ppm at 7 percent $O_2$ averaging 231 ppm for Unit 1 and 60 ppm for Unit 2. The inlet $SO_2$ concentration was not measured. Outlet HCl concentrations ranged from 7.8 to 176 ppm at 7 percent $O_2$ averaging 104 ppm for Unit 1 and 37 ppm for Unit 2. Removal efficiencies for HCl averaged 88 percent for Unit 1 and 94 percent for Unit 2. The inlet concentration of HCl for Unit 1 averaged 140 ppm higher over three runs than Unit 2, which may have led to the higher outlet acid concentrations for Unit 1 and lower HCl removal efficiency.

### TABLE 5-1. ACID GAS DATA FOR CLAREMONT

| Test Condition | Run Number[a] | FF Inlet Temperature (°F)[b] | Lime Feed Rate (lb/hr) | Inlet HCl Concentrations (ppmv, dry at 7% $O_2$) | Outlet Acid Gas Concentration (ppmv, dry at 7% $O_2$) | | HCl Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|
| | | | | | $SO_2$ | HCl | |
| Combustor = Normal<br>DSI/FF = Normal | 1-1 | 451 | 194 | 519 | 197 | 57.6 | 88.9 |
| | 1-2 | 452 | 194 | 1,070 | 337 | 176 | 83.6 |
| | 1-3 | 451 | 194 | 774 | 160 | 78.5 | 89.9 |
| Average (Unit 1) | | 451 | 194 | 788 | 231 | 104 | 87.5 |
| | 2-1 | 445 | 185 | 953 | 79.8 | 44.7 | 95.3 |
| | 2-2 | 452 | 185 | 471 | 62.5 | 35.0 | 92.6 |
| | 2-3 | 448 | 185 | 502 | 38.1 | 30.1 | 94.0 |
| Average (Unit 2) | | 448 | 185 | 642 | 60.1 | 36.6 | 94.0 |
| Combustor = Normal<br>DSI/FF = High lime feed | 1-4 | 448 | 222 | 462 | 31.4 | 7.8 | 98.3 |
| | 1-5 | 453 | 222 | 459 | 50.8 | 33.9 | 92.6 |
| | 1-6 | 454 | 222 | 424 | 31.6 | 29.4 | 93.1 |
| Average | | 452 | 222 | 448 | 37.9 | 23.7 | 94.7 |

[a] Run Number contains the unit number followed by the run number.

[b] Temperature estimated from measured value at the stack and an assumed temperature drop across the fabric filter (10°F).

The effect of lime feed rate was assessed from the data for Unit 1. By increasing the lime feed rate from 194 to 222 lb/hr, the HCl removal efficiency at Unit 1 increased by 7 percent to 94 percent and HCl and $SO_2$ emissions decreased by about 80 percent to 24 and 38 ppm, respectively. However, the HCl removal efficiency for Unit 2 at a lime feed rate of 185 lb/hr was similar to the HCl removal observed at Unit 1 with a lime feed rate of 222 lb/hr despite an inlet HCl concentration which was 200 ppm higher on average. Because of the widely varying inlet HCl concentrations and unknown inlet $SO_2$ concentration, conclusions about the effect of lime feed rate cannot be made. Nevertheless, over 85 percent HCl removal efficiency was achieved.

In Table 5-2, particulate data are presented. Six test runs were conducted; three on each unit. The outlet PM concentrations at Unit 1 ranged from 0.0095 to 0.012 at 12 percent $CO_2$ and averaged 0.011 gr/dscf. Outlet PM concentrations for Unit 2 were between 0.0027 and 0.0053 gr/dscf at 12 percent $CO_2$ and averaged 0.0043 gr/dscf. The flow rates at Unit 1 were approximately 3,500 acfm higher than at Unit 2, yielding 13 percent higher air-to-cloth ratios. This corresponds with the higher outlet PM concentrations measured for Unit 1. The fabric filter at Claremont operating at 440$^0$F can achieve outlet PM emissions of 0.01 gr/dscf at 12 percent $CO_2$, with hydrated lime injection into the duct.

Table 5-3 presents the CDD/CDF data from Claremont. Four test runs were conducted on Unit 1 at a FF inlet temperature of 437$^0$F and three on Unit 2 at 473$^0$F. At Unit 1, outlet CDD/CDF concentrations ranged from 21.4 to 45.8 ng/dscm at 7 percent $O_2$ and averaged 37.6 ng/dscm. At Unit 2, outlet CDD/CDF concentrations ranged from 24.4 to 39.9 ng/dscm and averaged 32.3 ng/dscm. Although the FF inlet temperatures for Unit 2 were about 36$^0$F higher than at Unit 1, there is no difference between CDD/CDF emissions.

### 5.2.2 Dutchess County[4]

The Dutchess County Resource Recovery facility in Poughkeepsie, New York, consists of two identical Westinghouse-O'Connor rotary waterwall mass burn combustor trains, each designed to combust 250 tons per day of MSW. Combustion gases exiting each combustor pass through heat recovery sections

TABLE 5-2. PARTICULATE DATA FOR CLAREMONT

| Test Condition | Run Number[a] | FF Inlet Temperature[b] (°F) | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1-1 | 440 | 31,570 | 0.011 |
| DSI/FF = Normal | 1-2 | 441 | 29,300 | 0.012 |
| | 1-3 | 440 | 29,110 | 0.0095 |
| Average (Unit 1) | | 440 | 29,993 | 0.011 |
| | 2-1 | 433 | 24,870 | 0.0048 |
| | 2-2 | 441 | 27,390 | 0.0053 |
| | 2-3 | 437 | 27,130 | 0.0027 |
| Average (Unit 2) | | 437 | 26,463 | 0.0043 |

[a] Run Number contains the unit number followed by the run number.

[b] Temperature estimated from measured value at the stack and an assumed temperature drop across the fabric filter (10°F).

## TABLE 5-3. CDD/CDF DATA FOR CLAREMONT

| Test Condition | Run Number[a] | FF Inlet Temperature (°F)[b] | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1-1 | 437 | 39.4 |
| DSI/FF = Normal | 1-2 | 448 | 43.9 |
| | 1-3 | 430 | 21.4 |
| | 1-4 | 431 | 45.8 |
| Average (Unit 1) | | 437 | 37.6 |
| | 2-2 | 478 | 39.9 |
| | 2-3 | 472 | 32.5 |
| | 2-4 | 469 | 24.4 |
| Average (Unit 2) | | 473 | 32.3 |

[a] Run Number contains the unit number followed by the run number.

[b] Temperature estimated from measured value at the stack and an assumed temperature drop across the fabric filter (10°F).

followed by a dry sorbent injection/fabric filter pollution control system. Following a spark arrestor, hydrated lime and Tesisorb® are injected into the flue gas through a Teller-designed venturi system. The lime injection rate is manually maintained at 125 to 150 lb/hr, but optimization tests are being planned which may alter this injection rate. The flue gas temperature at the injection point is typically about $400^{0}$F. Immediately following sorbent injection, flue gas enters a Zurn reverse-air fabric filter with fiberglass bags. The operating air-to-cloth ratio of the FF is 2 acfm/$ft^2$. The permitted outlet PM concentration for each unit is 0.015 gr/dscf at 12 percent $CO_2$. Flue gases from both units are exhausted through separate flues in a common stack.

Emission compliance tests were initially conducted at the Dutchess County RRF during January 31 through February 17, 1989. Additional testing was conducted on March 15 and 16, and May 24 and 25, 1989. During the January/February test, continuous $SO_2$ measurements were taken at the inlet and outlet to the pollution control system. In addition, flue gas at the FF outlet was analyzed for PM, HCl, CDD/CDF, HF, $NO_x$, metals (arsenic, beryllium, cadmium, chromium, lead, mercury, and nickel), and additional organic compounds at both units. Three runs were conducted for each pollutant. During the March test conducted to document improved PM removal, flue gas at the FF outlet was analyzed for PM and HCl (Unit 2 only) during three runs and by continuous monitor for $SO_2$ and CO on both units. The May test was conducted to demonstrate compliance of the facility with respect to PM (Unit 2 only) and CO.

In Table 5-4, HCl data are presented for all the HCl runs. Outlet HCl data from the three test runs in February at Unit 1 ranged from 2.4 to 70 ppm at 7 percent $O_2$, and averaged 30 ppm. At Unit 2 in February, four test runs at the outlet yielded concentrations ranging from 23 to 422 ppm, averaging 183 ppm. March testing of Unit 2 showed outlet HCl concentrations of 70 to 473 ppm for 6 runs and an average concentration of 200 ppm.

Outlet HCl concentrations were lower for Unit 1 than Unit 2. The high HCl values at Unit 2 may be due to clogging of the screw feeder for the hydrated lime and Tesisorb®. Because the feeder is manually operated, there

TABLE 5-4. HCl DATA FOR DUTCHESS COUNTY

| Test Conditions | Run Number[a] | FF Inlet Temperature (°F)[b] | Outlet HCl Concentration (ppm, dry at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1-1 | 379 | 70 |
| DSI/FF = Normal | 1-2 | 380 | 18 |
| (2/89 tests) | 1-3 | 383 | 2 |
| Average (Unit 1) | | 381 | 30 |
| Combustor = Normal | 2-1 | 354 | 209 |
| DSI/FF = Normal | 2-2 | 358 | 422 |
| (2/89 tests) | 2-3 | 377 | 78 |
| | 2-4 | 365 | 23 |
| Average (Unit 2) | | 364 | 183 |
| Combustor = Normal | 2-1 | 386 | 124 |
| DSI/FF = Normal | 2-2 | 399 | 70 |
| (3/89 tests) | 2-3 | 380 | 80 |
| | 2-4 | 363 | 200 |
| | 2-5 | 385 | 250 |
| | 2-6 | 377 | 473 |
| Average (Unit 2) | | 382 | 200 |

[a] Run number contains the unit number followed by the run number.

[b] Temperature estimated from a measured value at the stack and an assumed temperature drop of (10°F) across the fabric filter.

## TABLE 5-5. $SO_2$ CEM DATA FOR DUTCHESS COUNTY

| Test Condition | Unit Number | Date | Time[a] | FF Inlet Temperature (°F) | $SO_2$ Concentration (ppm dry at 7% $O_2$) |  | $SO_2$ Removal Efficiency (percent) |
|---|---|---|---|---|---|---|---|
|  |  |  |  |  | Inlet | Outlet |  |
| Combustor = Normal | 1 | 1/31 | 930 | 450 | 129 | 66 | 48.8 |
| DSI/FF = Normal |  |  | 1030 | 460 | 103 | 94 | 8.7 |
| (2/89 tests) |  |  | 1210 | 430 | 142 | 100 | 29.6 |
|  |  |  | 1300 | 390 | 109 | 85 | 22.0 |
|  |  |  | 1400 | 350 | 116 | 113 | 2.6 |
|  |  |  | 1500 | 350 | 114 | 69 | 39.5 |
|  |  |  | 1600 | 350 | 138 | 151 | -9.4 |
|  |  |  | 1700 | 360 | 167 | 137 | 18.0 |
|  |  |  | 1800 | 360 | 133 | 126 | 5.3 |
|  |  |  | 1900 | 370 | 112 | 158 | -41.1 |
|  |  |  | 2000 | 370 | 103 | 118 | -14.6 |
|  |  | 2/2 | 1410 | 430 | 188 | 198 | -5.3 |
|  |  |  | 1500 | NM[b] | 70 | 27 | 61.4 |
|  |  |  | 1600 | 450 | 72 | 26 | 63.9 |
| Average (Unit 1, 2/89) |  |  |  | 390 | 121 | 105 | 16.4 |
| Combustor = Normal | 2 | 2/1 | 1330 | NM | 118 | 81 | 31.4 |
| DSI/FF = Normal |  |  | 1430 | NM | 96 | 62 | 35.4 |
| (2/89 tests) |  |  | 1530 | NM | 87 | 86 | 1.2 |
|  |  |  | 1820 | NM | 133 | 184 | -38.4 |
|  |  | 2/2 | 950 | NM | 188 | 207 | -10.1 |
|  |  |  | 1120 | NM | 206 | 120 | 41.8 |
| Average (Unit 2, 2/89) |  |  |  | NM | 138 | 123 | 10.2 |
| Combustor = Normal | 1 | 3/16 | 1000 | NM | NM | 129 | -- |
| DSI/FF = Normal |  |  | 1100 | NM | NM | 104 | -- |
| (3/89 tests) |  |  | 1200 | NM | NM | 107 | -- |
|  |  |  |  | NM | NM | 111 | -- |
| Average (Unit 1, 3/89) |  |  |  | NM | NM | 105 | -- |
| Combustor = Normal | 2 | 3/15 | 1700 | NM | NM | 49 | -- |
| DSI/FF = Normal |  |  | 1800 | NM | NM | 106 | -- |
| (3/89 tests) |  |  | 1900 | NM | NM | 128 | -- |
|  |  | 3/16 | 1420 | NM | NM | 144 | -- |
|  |  |  | 1520 | NM | NM | 109 | -- |
|  |  |  | 1620 | NM | NM | 282 | -- |
| Average (Unit 2, 3/89) |  |  |  | NM | NM | 136 | -- |

[a] Starting time of hour for 1-hour average reported.

[b] NM = not measured.

is no means of knowing when the feeder clogs, which is reported to have happened occasionally.

Table 5-5 presents a summary of all the $SO_2$ data collected. Each $SO_2$ data point is a one-hour average of the one-minute averages collected with the continuous emission monitors. Outlet $SO_2$ concentrations ranged from 26 to 198 ppm at 7 percent $O_2$ at Unit 1 for 14 one-hour averages collected over two days in February, and averaged 105 ppm. Simultaneous inlet $SO_2$ concentrations during the February tests at Unit 1 ranged from 70 to 188 ppm and averaged 121 ppm. At the outlet of Unit 1 during the March tests, three one-hour averages of 129, 104, and 101 ppm were reported, for an average concentration of 111 ppm. No inlet data were collected during the March tests. Removal efficiencies for $SO_2$ during the February tests ranged from -42 to 64 percent and averaged 16 percent. There is no certain cause of the negative removal efficiencies, but they may be due to differences in the instruments used to collect the data.

At Unit 2, outlet $SO_2$ concentrations ranged from 62 to 207 ppm for 6 one-hour averages during February and averaged 123 ppm. At the inlet of Unit 2 during February, $SO_2$ concentrations ranged from 87 to 206 ppm for the same period and averaged 138 ppm. The $SO_2$ removal efficiency ranged from -38 to 42 percent and averaged 10 percent. During March, the outlet $SO_2$ concentration ranged from 49 to 282 ppm for 6 one-hour averages and averaged 136 ppm.

$SO_2$ performance was similar for the two units. Although the average outlet emissions from Unit 1 were about 20 ppm lower than from Unit 2, the inlet concentrations were also lower by about 20 ppm. $SO_2$ removal efficiencies were similar for the two units. Temperature at the FF inlet did not affect performance for $SO_2$, as emissions were widely scattered, irrespective of temperature. Figure 5-1 graphs outlet $SO_2$ concentrations as a function of inlet $SO_2$ concentration. While there is a wide scatter in the data, a trend of increasing outlet $SO_2$ concentration with increasing inlet $SO_2$ concentration can be observed. For Unit 1, the lowest inlet $SO_2$ concentration, 70 ppm, corresponded to the lowest outlet $SO_2$ concentration, 30 ppm, and the highest inlet $SO_2$ concentration, 188 ppm, was also coincident with the highest outlet $SO_2$ concentration, 198 ppm.

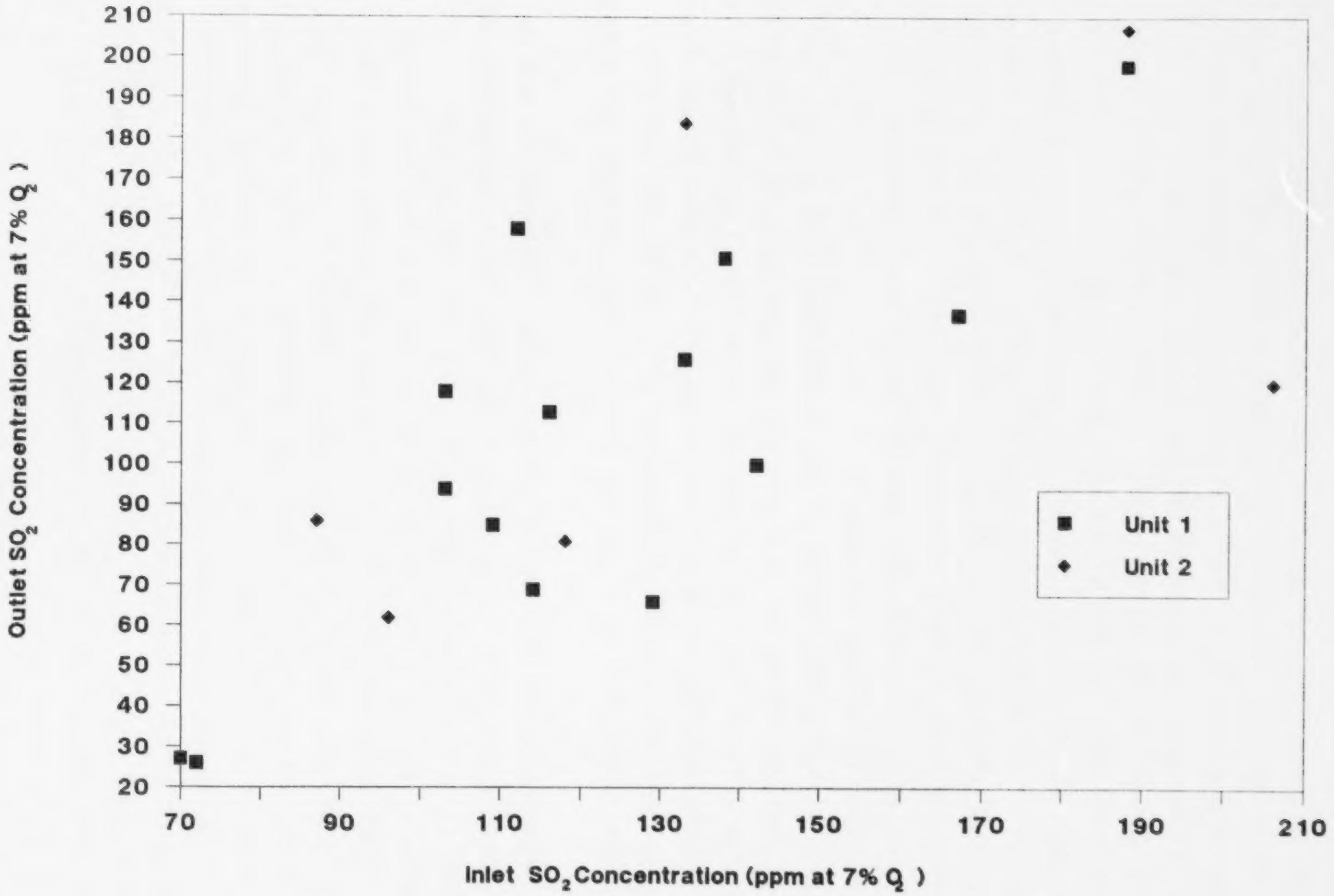


Figure 5-1. Outlet $SO_2$ concentration as a function of inlet $SO_2$ concentration at Dutchess County.

In Table 5-6, particulate data are presented. The outlet PM concentrations at Unit 1 ranged from 0.004 to 0.015 gr/dscf at 12 percent $CO_2$ and averaged 0.0097 gr/dscf. Outlet PM concentrations for Unit 2 were between 0.030 and 0.037 gr/dscf at 12 percent $CO_2$ and averaged 0.035 gr/dscf for the February tests. After the February tests on Unit 2 failed to demonstrate compliance with permit conditions, repairs and modifications were made to the Unit 2 fabric filter. Broken bags were replaced, the cleaning cycle time was reduced, and all particulate conveyors and hoppers were cleared of built-up ash. For the March tests at Unit 2, outlet PM concentrations ranged from 0.005 to 0.027 gr/dscf and averaged 0.011 gr/dscf The outlet PM concentration for the May compliance tests on Unit 2 ranged from 0.007 to 0.009 gr/dscf at 12 percent $CO_2$. Thus, both units were able to demonstrate outlet PM levels less than the permit level of 0.015 gr/dscf.

Table 5-7 presents the metals data from the three test runs at each of the two units at Dutchess County. Outlet metals concentrations were consistently low and similar between the two units for all metals except mercury. Arsenic was not detected at either unit. Cadmium, chromium, and nickel concentrations averaged less than 12 ug/dscm at 7 percent $O_2$ at both units. Lead concentrations averaged 39 ug/dscm at Unit 1 and 49 ug/dscm at Unit 2. Similar outlet concentrations were observed at both units even though outlet PM levels were substantially higher at Unit 2 during the same testing period. The observed outlet concentrations, compared to typical uncontrolled metals concentrations (Section 1.2), indicate removal efficiencies of greater than 99 percent for arsenic, cadmium, chromium, lead, and nickel.

Mercury exhibited higher outlet concentrations than the other metals and showed wide variation between facilities. At Unit 1, the outlet mercury concentration averaged 1,080 ug/dscm at a FF inlet temperature of $430^{\circ}F$ while at Unit 2, the average concentration was 85 ug/dscm at a FF inlet temperature of $365^{\circ}F$. The $65^{\circ}F$ lower fabric filter inlet temperature at Unit 2 than at Unit 1 may have contributed to the difference.

## TABLE 5-6. PARTICULATE DATA FOR DUTCHESS COUNTY

| Test Condition | Run Number[a] | FF Inlet Temperature (°F)[b] | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1-1 | 379 | 39,700 | 0.015 |
| DSI/FF = Normal | 1-2 | 380 | 42,600 | 0.010 |
| (2/89 tests) | 1-3 | 383 | 42,000 | 0.0038 |
| Average (Unit 1) | | 381 | 41,400 | 0.0097 |
| Combustor = Normal | 2-1 | 354 | 42,600 | 0.037 |
| DSI/FF = Normal | 2-2 | 358 | 42,200 | 0.037 |
| (2/89 tests) | 2-3 | 372 | 43,300 | 0.030 |
| | 2-4 | 365 | 42,900 | 0.034 |
| Average (Unit 2) | | 364 | 42,800 | 0.035 |
| Combustor = Normal | 2-1 | 386 | 44,300 | 0.0069 |
| DSI/FF = Normal | 2-2 | 399 | 44,900 | 0.027 |
| (3/89 tests) | 2-3 | 380 | 38,600 | 0.012 |
| | 2-4 | 363 | 42,800 | 0.0051 |
| | 2-5 | 385 | 44,400 | 0.0077 |
| | 2-6 | 377 | 42,700 | 0.0073 |
| Average (Unit 2) | | 382 | 43,000 | 0.011 |
| Combustor = Normal | 2-1 | 377 | 48,900 | 0.0080 |
| DSI/FF = Normal | 2-2 | 382 | 49,400 | 0.0072 |
| (5/89 tests) | 2-3 | 389 | 49,100 | 0.0087 |
| Average (Unit 2) | | 383 | 49,100 | 0.0079 |

---

[a] Run Number contains the unit number followed by the run number.

[b] Temperature estimated from measured value at the stack and an assumed temperature drop across the fabric filter (10°F).

TABLE 5-7. METALS DATA FOR DUTCHESS COUNTY

| Test Condition | Run[a] Number | FF Inlet Temperature (°F)[b] | Outlet PM Concentration (gr/dscf at 12% $CO_2$)[c] | Outlet Concentration ($\mu$g/dscm at 7% $O_2$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal | 1-1 | 426 | -- | ND[d] | 1.76 | 3.16 | 32.7 | 888 | 2.54 |
| DSI/FF = Normal | 1-2 | 435 | -- | ND | 2.76 | 16.8 | 39.7 | 1,180 | 22.8 |
| (2/89 tests) | 1-3 | 428 | -- | ND | 3.64 | 4.85 | 44.2 | 1,160 | 8.11 |
| Average (Unit 1) | | 430 | 0.0097 | ND | 2.72 | 8.27 | 38.9 | 1,080 | 11.2 |
| Combustor = Normal | 2-1 | 352 | -- | ND | 1.11 | 11.3 | 23.1 | 35.6 | 14.5 |
| DSI/FF = Normal | 2-2 | 367 | -- | ND | 4.49 | 4.63 | 75.4 | 95.6 | 4.45 |
| (2/89 tests) | 2-3 | 377 | -- | ND | 3.48 | 3.51 | 48.9 | 123 | 3.46 |
| Average (Unit 2) | | 365 | 0.035 | ND | 3.03 | 6.48 | 49.1 | 84.7 | 7.47 |

[a] Run Number contains the unit number followed by the run number.

[b] Temperature estimated from measured value at the stack and an assumed temperature drop across the FF (10°F).

[c] Particulate data not collected simultaneously with metals. Average PM concentration for the same test period reported.

[d] ND - not detected.

However, because the inlet mercury concentrations are unknown and because of previously observed variability in uncontrolled mercury concentrations, it cannot be determined how much of the lower mercury concentrations at Unit 2 are a result of FF performance rather than decreased inlet mercury levels.

Table 5-8 presents the CDD/CDF data from the three runs at each unit. At Unit 1, outlet CDD/CDF concentrations ranged from 3.73 to 5.97 ng/dscm at 7 percent $O_2$ and averaged 4.83 ng/dscm. At Unit 2, outlet CDD/CDF concentrations ranged from 17.5 to 18.5 ng/dscm and averaged 17.4 ng/dscm. Unit 1 operated at a FF inlet temperature $10^{o}$F less than Unit 2 (378 versus $387^{o}$F). There is insufficient information to explain the lower CDD/CDF concentrations from Unit 1.

### 5.2.3 Quebec City[5]

The Quebec City, Canada, municipal waste combustion facility contains four separate waterwall combustors. The combustors were originally built in 1975 with Von Roll reciprocating grates. Waterwall arches were added to each combustion chamber in 1979. Each unit is designed to combust 250 tons/day of MSW. Emissions were originally controlled by 2-field ESP's.

Environment Canada, in cooperation with Flakt Canada, LTD., established an extensive test program to evaluate the capability of a pilot-scale duct sorbent injection/fabric filter control system to remove PM, $SO_2$, HCl, heavy metals, CDD/CDF, and other organic compounds. Flakt constructed a pilot-scale DSI/FF facility at the Quebec City Plant equipped with:

(1) a flue gas slipstream from the ESP inlet of Unit 3 to deliver 2,000 $ft^3$/min at $500^{o}$F to the pilot facility;

(2) a water spray quench chamber where water is sprayed concurrently with the flue gas to cool the flue gas to less than $230^{o}$F;

(3) a sorbent injection chamber with a single, dry hydrated lime injection nozzle and an internal cyclone at the entrance to the chamber; and

(4) a pulse-cleaned FF using high-temperature teflon bags with an air-to-cloth ratio of 4.4 acfm/$ft^2$.

## TABLE 5-8. CDD/CDF DATA FOR DUTCHESS COUNTY

| Test Conditions | Run Number[a] | FF Inlet Temperature[b] (°F) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1-1 | 378 | 5.97 |
| DSI/FF = Normal | 1-2 | 380 | 4.78 |
| (2/89 tests) | 1-3 | 376 | 3.73 |
| Average (Unit 1) | | 378 | 4.83 |
| Combustor = Normal | 2-1 | 378 | 17.6 |
| DSI/FF = Normal | 2-2 | 379 | 17.5 |
| (2/89 tests) | 2-3 | 384 | 18.5 |
| Average (Unit 2) | | 387 | 17.9 |

[a] Run number contains the unit number followed by the run number.

[b] Temperature estimated from a measured value at the stack and an assumed temperature drop of (10°F) across the fabric filter.

Testing was conducted with the pilot-scale DSI/FF system in March 1985. The results of tests with a pilot spray dryer/fabric filter at Quebec City are reported in Section 7.2. Results of the tests of the full-scale ESP at Quebec City are reported in Section 2.2.1.9.

The DSI/FF tests were conducted at a single lime feed rate and temperatures of 230 to 400°F at the FF inlet. Flue gas was sampled simultaneously at the water quench chamber inlet, FF inlet, and FF outlet, and analyzed for HCl, $SO_2$, metals (arsenic, cadmium, chromium, mercury, lead, and nickel), CDD/CDF, and other organics. Metals data were not taken at the mid-point sampling location. PM data were collected only at the inlet sampling location and are not reported here.

Acid gas data are presented in Table 5-9. Nine test runs were conducted at average fabric filter inlet temperatures of 400, 285, 250, and 231°F. The constant lime feed rate resulted in stoichiometric ratios ranging from 1.2 to 1.5. The inlet concentrations of acid gases remained relatively consistent during each condition. At a FF inlet temperature setpoint of 392°F, two runs were conducted. Outlet $SO_2$ concentrations were 90 and 100 ppm, for an average of 95 ppm. $SO_2$ removal efficiency was relatively consistent and averaged 23 percent. Outlet HCl concentrations were 88 and 122 ppm, for an average of 105 ppm. HCl removal efficiency was relatively consistent and averaged 76 percent. At a FF inlet temperature setpoint of 284°F, three runs were conducted. Outlet $SO_2$ concentrations ranged from 13 to 45 ppm and averaged 34 ppm. The $SO_2$ removal efficiency varied from 58 to 92 percent and averaged 73 percent. Outlet HCl concentrations ranged from 23 to 35 ppm and averaged 30 ppm. HCl removal efficiencies varied little and averaged 93 percent. At a FF inlet temperature setpoint of 257°F, two runs were conducted. Outlet $SO_2$ concentrations were 14 and 7 ppm, for an average of 11 ppm. The average $SO_2$ removal efficiency was 92 percent. Outlet HCl concentrations were 9 and 11 ppm. The average HCl removal efficiency was 98 percent for both runs. At a FF inlet temperature setpoint of 230°F, two runs were conducted. Outlet $SO_2$ concentrations were 4 and 6 ppm. $SO_2$ removal efficiency was

## TABLE 5-9. ACID GAS DATA FOR QUEBEC CITY PILOT DSI/FF

| Test Condition | Run Number | FF Inlet Temperature (°F) | Stoichiometric Ratio | Acid Gas Concentrations (ppmv, dry at 7% $O_2$) | | | | | | Quench Chamber Removal (%) | | FF Removal (%) | | Overall Acid Gas Removal (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Inlet | | Midpoint | | Outlet | | | | | | | |
| | | | | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl |
| Combustor = Normal | 5 | 400 | 1.6 | 126 | 422 | 112 | 211 | 90 | 88 | 11 | 50 | 20 | 54 | 29 | 77 |
| DSI/FF at 392°F FF | 6 | 400 | 1.4 | 122 | 481 | 98 | 251 | 100 | 122 | 20 | 48 | - 3 | 52 | 18 | 75 |
| inlet temperature | | | | | | | | | | | | | | | |
| Average | | 400 | 1.5 | 124 | 451 | 105 | 231 | 95 | 105 | 15 | 49 | 9 | 53 | 23 | 76 |
| Combustor = Normal | 1 | 285 | 1.2 | 148 | 458 | -- | 141 | 44 | 35 | -- | 69 | -- | 75 | 70 | 92 |
| DSI/FF at 284°F FF | 2 | 287 | 1.4 | 158 | 400 | 115 | 142 | 13 | 23 | 27 | 64 | 88 | 83 | 92 | 94 |
| inlet temperature | 11 | 284 | 1.2 | 107 | 512 | 70 | 139 | 45 | 31 | 35 | 93 | 36 | 78 | 58 | 94 |
| Average | | 285 | 1.3 | 138 | 457 | 92 | 141 | 34 | 30 | 31 | 69 | 62 | 79 | 73 | 93 |
| Combustor = Normal | 3 | 250 | 1.2 | 148 | 470 | 82 | 93 | 14 | 9 | 45 | 80 | 82 | 90 | 90 | 98 |
| DSI/FF at 257°F FF | 4 | 250 | 1.1 | 108 | 530 | 59 | 55 | 7 | 11 | 46 | 90 | 87 | 79 | 93 | 98 |
| inlet temperature | | | | | | | | | | | | | | | |
| Average | | 250 | 1.2 | 128 | 500 | 70 | 74 | 11 | 10 | 45 | 85 | 85 | 85 | 92 | 98 |
| Combustor = Normal | 12 | 229 | 1.2 | 128 | 509 | 29 | 4 | 4 | 8 | 77 | 99 | 86 | -85 | 97 | 98 |
| DSI/FF at 230°F FF | 13 | 232 | 1.3 | 129 | 404 | 23 | 28 | 6 | 7 | 82 | 93 | 76 | 75 | 96 | 98 |
| inlet temperature | | | | | | | | | | | | | | | |
| Average | | 231 | 1.3 | 129 | 456 | 26 | 16 | 5 | 7 | 80 | 96 | 81 | - 5 | 96 | 98 |

consistent between the two runs and averaged 96 percent. Outlet HCl concentrations for the two runs were 8 and 7 ppm. HCl removal efficiency was 98 percent for both runs.

In Figure 5-2, $SO_2$ removal efficiency is shown as a function of FF inlet temperature. Generally, $SO_2$ removal efficiency increased as temperature decreased. Similar phenomena is observed with HCl, as shown in Figure 5-3, although the amount of increase is not as great. HCl removal efficiencies above 90 percent were demonstrated at FF inlet temperatures of $285^{o}F$ or less.

The amount of $SO_2$ and HCl removal across the water quench chamber increased as the FF inlet temperature decreased. For $SO_2$, the removal efficiency across the quench chamber increased from about 15 percent at a FF inlet temperature of $400^{o}F$ to about 80 percent at a FF inlet temperature of $230^{o}F$, while for HCl, the removal efficiency across the quench chamber at the same temperature increased from 50 to about 95 percent. Acid gas removal efficiencies across the FF showed some variation with temperature, but not nearly as much as the removal across the SD. At $400^{o}F$ at the FF inlet, $SO_2$ removal efficiency across the FF was 20 percent for Run 5 and -3 percent for Run 6. The negative removal efficiency indicates little or no $SO_2$ removal, as the midpoint and outlet $SO_2$ concentrations differed by only 2 ppm (within analytical error). At the same temperature, HCl removal efficiency across the FF averaged 53 percent. At $284^{o}F$ at the FF inlet, $SO_2$ removal efficiency was 88 and 36 percent and HCl removal efficiency averaged 79 percent. At 257 and $230^{o}F$ FF inlet temperatures, $SO_2$ and HCl removal efficiencies across the FF were consistently about 85 percent except for Run 12 at $230^{o}F$. A negative removal efficiency was obtained for HCl after an unusually low HCl concentration was measured at the midpoint (4 ppm). Because the value was so low, additional removal across the FF could not be easily measured, because the accuracy of instruments decreases at such low concentrations. Thus, the negative value probably indicates little or no HCl removal across the FF.

Thus, based on analyses of the acid gas data, temperature appears to significantly affect both $SO_2$ and HCl removal efficiency for a DSI/FF system, although the effect is more pronounced for $SO_2$.

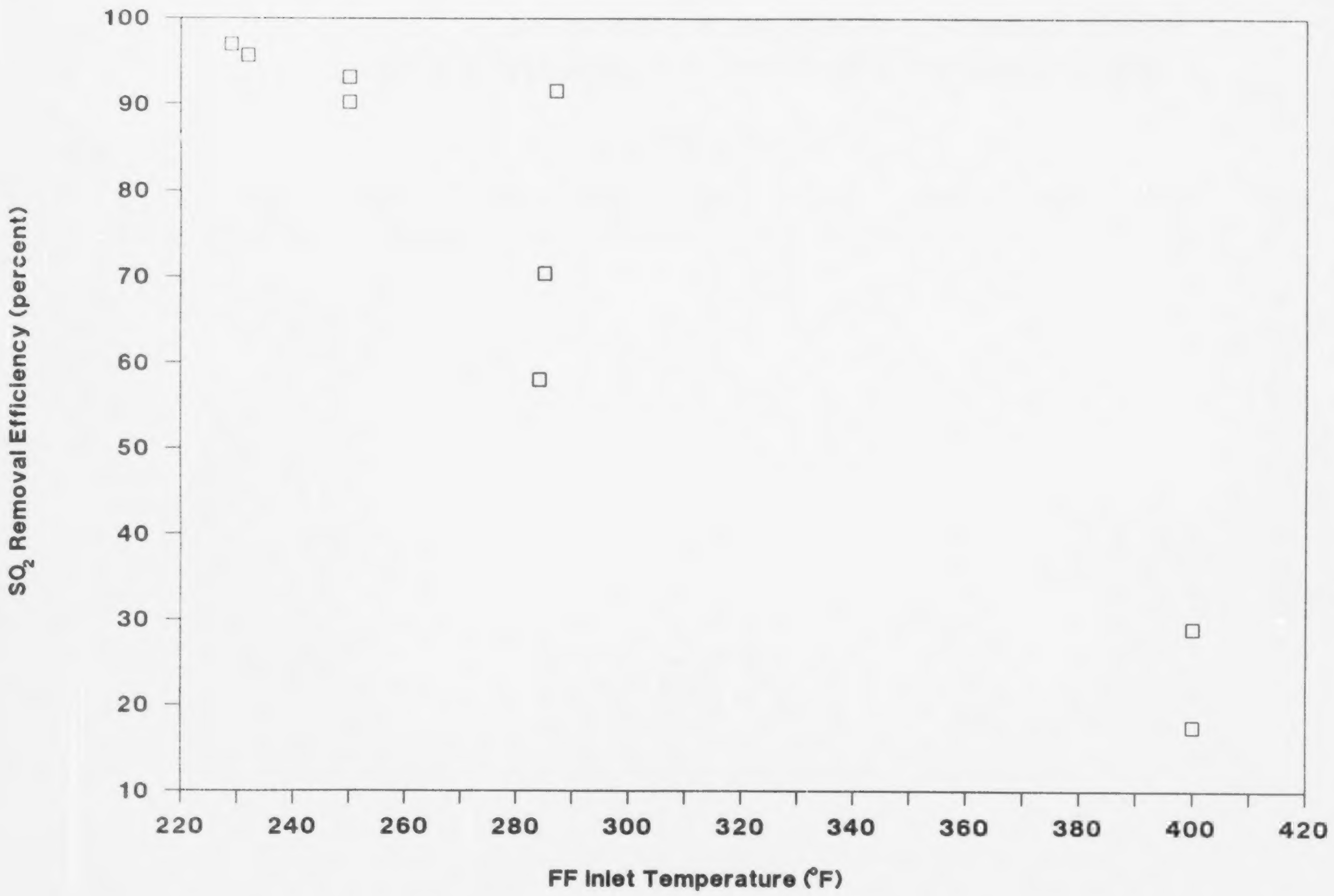


Figure 5-2. $SO_2$ removal efficiency as a function of FF inlet temperature at the Quebec City DSI/FF system.

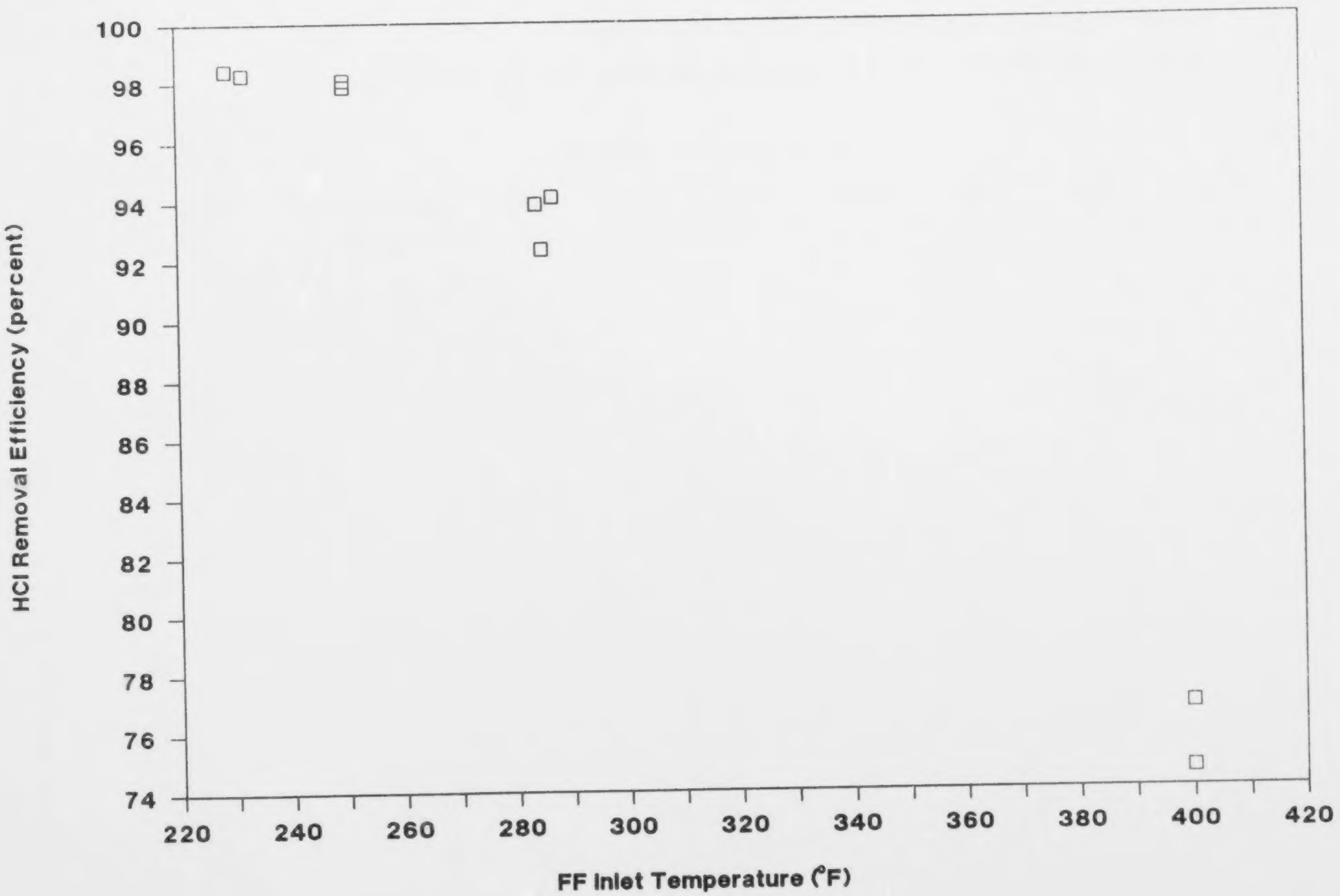


Figure 5-3. HCl removal efficiency as a function of FF inlet temperature at the Quebec City DSI/FF system.

Metals data for the nine test runs are presented in Table 5-10. Removal efficiencies for arsenic, cadmium, chromium, lead, and nickel were above 99.9 percent for all test conditions. Mercury removal was consistently above 85 percent for all test runs at FF inlet temperatures below 285°F. At 400°F, no mercury removal occurred. Although outlet mercury concentrations were greater than the inlet values, there is no apparent reason for these differences.

CDD/CDF data are presented in Table 5-11 for the eight runs conducted. Run 2 samples were lost prior to analysis. Outlet CDD/CDF concentrations ranged from not detected to 9.0 ng/dscm at 7 percent $O_2$ and removal efficiencies were at least 99.7 percent for all test runs. At temperatures below 285°F, 35 to 65 percent of the CDD/CDF removal occurred across the quench chamber. At 400°F, no CDD/CDF removal occurred across the quench chamber. Removal across the FF was consistently above 99.5 percent. Thus, decreasing the FF inlet temperature to below 285°F will decrease CDD/CDF emissions with the DSI/FF system at Quebec City.

### 5.2.4 Springfield[6]

The Springfield Resource Recovery Facility in Agawam, Massachusetts, consists of three identical Vicon Recovery Systems modular combustors, each designed to combust 120 tons/day of MSW. Flue gas from the combustor trains is cooled through heat recovery to about 280°F at a flow rate of 24,000 acfm. Dry hydrated lime is pneumatically injected into the flue gas downstream of the heat recovery in a reactor chamber which is sited to provide for about one second of residence time. The design lime feed rate is 83 lb/hr. The reaction products, fly ash, and unreacted sorbent are collected in a pulse-jet cleaned fabric filter with 4 compartments of 126 bags each. The bags are made of teflon coated fiberglass and provide a net air-to-cloth ratio of 2.9 acfm/ft$^2$. Flue gases are exhausted through a common stack.

The initial compliance testing at Springfield in October 1988 is summarized below. Three test runs were conducted at the common stack for each of the following pollutants: $SO_2$, HCl, PM, trace metals, (arsenic, cadmium, chromium, lead, mercury, and nickel) and CDD/CDF. The outlet $SO_2$ concentration averaged 23 ppm, with an average removal efficiency of

TABLE 5-10. METALS DATA FOR QUEBEC CITY PILOT DSI/FF

| Test Condition | Run | FF Inlet Temperature (°F)[a] | Outlet PM Concentration (gr/dscf at 7% $O_2$)[a] | Inlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Removal Efficiency (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal | 5 | 400 | -- | 85 | 1,007 | 1,784 | 35,689 | 501 | 826 | 0.10 | 1.22 | ND[b] | 5.34 | 776 | 1.00 | 99.9 | 99.9 | 100 | 99.98 | -54.9 | 99.9 |
| DSI/FF = 392°F inlet | 6 | 400 | -- | 70 | 1,020 | 1,979 | 33,870 | 400 | 843 | 0.04 | ND | 1.03 | 7.25 | 451 | 2.07 | 99.94 | 100 | 99.95 | 99.98 | -12.8 | 99.8 |
| Average | | 400 | -- | 78 | 1,014 | 1,882 | 34,780 | 451 | 835 | 0.07 | 0.61 | 0.50 | 6.30 | 614 | 1.54 | 99.92 | 99.93 | 99.95 | 99.98 | -33.9 | 99.9 |
| Combustor = Normal | 1 | 285 | -- | NM[c] | NM | NM | NM | NM | NM | 0.12 | ND | 2.41 | 9.64 | 8.0 | 2.41 | -- | -- | -- | -- | -- | -- |
| DSI/FF = 284°F inlet | 2 | 287 | -- | 174 | 2,008 | 2,873 | 36,942 | 289 | 1,890 | 0.04 | ND | 2.02 | 8.07 | 8.5 | 1.00 | 99.98 | 100 | 99.9 | 99.98 | 97.1 | 99.5 |
| | 11 | 284 | -- | 90 | 1,028 | 1,180 | 31,264 | 351 | 629 | 0.04 | ND | ND | 1.22 | 31.1 | 0.41 | 99.95 | 100 | 100 | 100 | 91.1 | 99.9 |
| Average | | | | 132 | 1,518 | 2,027 | 34,103 | 320 | 1,260 | 0.07 | ND | 1.48 | 6.31 | 15.9 | 1.27 | 99.97 | 100 | 99.9 | 99.98 | 99.1 | 99.9 |
| Combustor = Normal | 3 | 250 | -- | 103 | 1,340 | 1,918 | 44,537 | 428 | 1,777 | 0.04 | 0.44 | 0.44 | 2.66 | 0.9 | 0.44 | 99.97 | 99.97 | 99.98 | 99.99 | 99.8 | 99.98 |
| DSI/FF = 257°F inlet | 4 | 250 | -- | NM | NM | NM | NM | 531 | NM | ND | 0.42 | 2.51 | 2.51 | 24.5 | 4.18 | -- | -- | -- | -- | 95.4 | -- |
| Average | | | | 103 | 1,340 | 1,918 | 44,537 | 480 | 1,777 | 0.02 | 0.43 | 1.48 | 2.59 | 12.7 | 2.31 | 99.97 | 99.97 | 99.98 | 99.99 | 97.6 | 99.98 |
| Combustor = Normal | 12 | 229 | -- | 147 | 1,277 | 3,087 | 41,128 | 208 | 980 | 0.02 | 0.44 | 0.44 | 3.94 | 30.9 | 1.32 | 99.99 | 99.97 | 99.99 | 99.99 | 85.1 | 99.9 |
| DSI/FF = 230°F inlet | 13 | 232 | -- | 272 | 957 | 1,531 | 30,587 | 681 | 886 | NM | NM | NM | NM | 48.6 | NM | -- | -- | -- | -- | 92.9 | -- |
| Average | | | | 195 | 1,117 | 2,309 | 25,858 | 445 | 933 | 0.02 | 0.44 | 0.44 | 3.94 | 39.8 | 1.32 | 99.99 | 99.97 | 99.99 | 99.99 | 89.0 | 99.9 |

[a] Outlet PM not measured during metals runs. All concentrations below detection limit during preliminary tests of the system.

[b] ND = not detected.

[c] NM = not measured.

TABLE 5-11. CDD/CDF DATA FOR QUEBEC CITY PILOT DSI/FF

| Test Conditions | Run Number | FF Inlet Temperature (°F) | CDD/CDF Concentration (ng/dscm at 7% $O_2$) | | | Quench Chamber CDD/CDF Removal (%) | FF CDD/CDF Removal (%) | Overall CDD/CDF Removal (%) |
|---|---|---|---|---|---|---|---|---|
| | | | Inlet | Midpoint | Outlet | | | |
| Combustor = Normal DSI/FF at 392°F inlet temperature | 5 | 400 | 1,820 | 1,903 | 8.99 | -4.52 | 99.5 | 99.5 |
| | 6 | 400 | 1,374 | 1,373 | 5.68 | 0.07 | 99.6 | 99.6 |
| Average | | 400 | 1,597 | 1,638 | 7.33 | -4.45 | 99.6 | 99.6 |
| Combustor = Normal DSI/FF at 284°F FF inlet temperature[c] | 1 | 285 | 2,281 | NM[a] | ND[b] | -- | -- | 100 |
| | 11 | 284 | 2,272 | 1,176 | 0.97 | 48.3 | 99.9 | 99.96 |
| Average | | 285 | 2,277 | 1,176 | 0.49 | 48.3 | 99.9 | 99.96 |
| Combustor = Normal DSI/FF at 257°F FF inlet temperature | 3 | 250 | 1,958 | 1,079 | ND | 44.9 | 100 | 100 |
| | 4 | 250 | 2,766 | 934 | ND | 66.2 | 100 | 100 |
| Average | | 250 | 2,361 | 1,007 | ND | 55.6 | 100 | 100 |
| Combustor = Normal DSI/FF at 230°F FF inlet temperature | 12 | 229 | 1,018 | 753 | 3.59 | 26.0 | 99.5 | 99.7 |
| | 13 | 232 | 756 | 413 | 1.28 | 45.4 | 99.7 | 99.8 |
| Average | | 231 | 887 | 456 | 2.43 | 35.7 | 99.6 | 99.7 |

[a] NM = not measured

[b] ND = not detected.

[c] Run 2 samples lost.

83 percent. The outlet HCl concentration averaged 33 ppm, with an average removal efficiency of 94 percent. The outlet PM concentration was 0.0016 gr/dscf, with a removal efficiency of 99.8 percent. Outlet metals were measured from which a removal efficiency was estimated assuming typical uncontrolled metals concentrations. For arsenic, cadmium, and lead, outlet concentrations of not detected, 1, and 21 ug/dscm, respectively, indicate removal efficiencies of greater than 99 percent. Outlet chromium and nickel concentrations of 10 and 24 ug/dscm, respectively, suggest removal efficiencies of at least 97 percent. Outlet mercury emissions were 300 ug/dscm, indicating approximately 70 percent removal efficiency. The total CDD/CDF concentration was not reported in the data summary, but the 2378-TCDD toxic equivalency of 0.09 ng/dscm at 7 percent $O_2$ was given.

### 5.2.5 St. Croix[7-11]

The St. Croix Waste to Energy Facility in New Richmond, Wisconsin, consists of three identical Cadoux modular, excess air combustors each designed to combust 38 tons/day of MSW. Flue gas from each of the three combustors passes through steam boilers, and is then combined and routed to a dual hydrated lime injection system manufactured by Interel Corporation.

Hydrated lime is injected into the flue gas at a maximum rate of 100 lb/hr upstream of two parallel air-to-air heat exchangers that cool the flue gas from 400 to 250°F or less. The flue gas then flows upward through parallel reactor vessels that provide additional contact time before entering the fabric filters. At the bottom of the union of the reactor vessels, there is a drum of ceramic balls which break up particulate clumps as the flue gas passes through. Recirculated fabric filter ash can be injected into the reactor vessels if desired.

The fabric filters are pulse-jet cleaned horizontal bag units which provide a surface area of 4,844 $ft^2$ each at a flue gas flow of about 14,500 acfm each. Air-to-cloth ratio is about 3 $acfm/ft^2$. The flue gas exiting the fabric filters is combined and exhausted through a common stack.

Several tests have been conducted at the St. Croix MWC. In all of these tests, the combustor was operated normally with very high excess air rates which required large correction factors to normalize the data. In

June 1988, compliance testing was conducted at the FF outlet. The DSI system was operated with the maximum lime injection rate of 100 lb/hr and maximum ash recirculation ratio, 16 times the flyash and lime loading to th FF without recirculation. Flue gas was analyzed for $SO_2$, HCl, PM, metals (arsenic, cadmium, chromium, lead, mercury, and nickel), and CDD/CDF. Simultaneous $SO_2$ and HCl measurements were taken at the DSI/FF system to characterize system performance. In August 1988, additional testing was conducted with $SO_2$ and HCl measured simultaneously at the inlet and outlet of the DSI/FF system to again characterize system performance. The lime feed rate was maintained at 100 lb/hr, but the recirculation ratio was decreased to 3.5. In October 1988, particulate emissions were measured at the FF outlet because the system had not met the permit requirements for PM in June. Three test runs to again demonstrate system performance for $SO_2$ and HCl were also conducted in October. The lime feed rate was halved (53 lb/hr) during two runs, and all three runs were without ash recirculation. Flue gas samples were collected and analyzed for $SO_2$ and HCl at the DSI inlet, the two FF inlet locations, and the FF outlet.

In Table 5-12, acid gas data from all three test programs for the DSI/FF inlet and outlet sampling locations are presented. The data consist of nine separate test runs. All tests were conducted at the same FF inlet temperature of $250^0$F. During testing in June with 100 lb/hr of lime and ash recycle ratio of 16, outlet $SO_2$ concentrations ranged from 15 to 58 percent at 7 percent $O_2$ and averaged 34 ppm. $SO_2$ removal efficiencies ranged from 64 to 94 percent and averaged 78 percent. Outlet HCl concentrations ranged from 0.34 to 1.5 ppm and averaged 0.75 ppm. HCl removal efficiencies were all greater than 99.7 percent. In August, with 100 lb/hr of lime and a recycle ratio of 3.5, outlet $SO_2$ concentrations ranged from 2 to 8 ppm and averaged 5 ppm. Corresponding $SO_2$ removal efficiencies ranged from 89 to 97 percent and averaged 93 percent. HCl was not detected in any of the three runs, for a removal efficiency of at least 99.97 percent. The single October test run with 100 lb/hr of lime and no ash recycle resulted in not detected outlet $SO_2$ and HCl concentrations. The removal efficiencies were at least 98.7 percent for $SO_2$ and 99.99 percent for HCl. The last two October test tuns with 53 lb/hr of lime and no ash recycle resulted in

TABLE 5-12. ACID GAS DATA FOR ST. CROIX

| Test Condition | Run Number | FF Inlet Temperature (°F) | Stoichiometric Ratio | Acid Gas Concentration (ppm, dry at 7% $O_2$) Inlet $SO_2$ | Inlet HCl | Outlet $SO_2$ | Outlet HCl | Acid Gas Removal Efficiency (%) $SO_2$ | HCl |
|---|---|---|---|---|---|---|---|---|---|
| Combustor = Normal | 1 | 250 | 2.2 | 250 | 479 | 15 | 0.34 | 94.0 | 99.93 |
| DSI/FF | 2 | 250 | 3.6 | 117 | 472 | 30 | 0.42 | 74.4 | 99.91 |
| Lime feed = 100 lb/hr | 3 | 250 | 2.8 | 163 | 507 | 58 | 1.5 | 64.4 | 99.7 |
| Ash recycle rate = 16 | | | | | | | | | |
| Average | | 250 | 2.9 | 177 | 486 | 34 | 0.75 | 77.6 | 99.9 |
| Combustor = Normal | 1 | 250 | 3.5 | 74 | 426 | 5 | ND[a] | 92.9 | >99.97 |
| DSI/FF | 2 | 250 | 3.3 | 81 | 524 | 2 | ND[a] | 97.4 | >99.97 |
| Lime feed = 100 lb/hr | 3 | 250 | 2.8 | 82 | 529 | 8 | ND[a] | 89.4 | >99.97 |
| Ash recycle rate = 3.5 | | | | | | | | | |
| Average | | 250 | 3.2 | 79 | 493 | 5 | ND[a] | 93.3 | >99.97 |
| Combustor = Normal | 1 | 250 | 2.3 | 86 | 706 | ND[b] | ND[c] | 98.7 | >99.99 |
| DSI/FF | | | | | | | | | |
| Lime feed = 100 lb/hr | | | | | | | | | |
| No ash recycle | | | | | | | | | |
| Combustor = Normal | 2 | 250 | 1.1 | 81 | 816 | 23 | ND[c] | 71.7 | >99.99 |
| DSI/FF | 3 | 250 | 1.2 | 116 | 669 | 33 | ND[c] | 71.6 | >99.99 |
| Lime feed = 53 lb/hr | | | | | | | | | |
| No ash recycle | | | | | | | | | |
| Average | | 250 | 1.2 | 99 | 743 | 28 | ND[c] | 71.7 | >99.99 |

[a] Not detected. Detection limit = 0.016 ppm at 7 percent $O_2$.

[b] Not detected. Detection limit = 1.5 ppm at 7 percent $O_2$.

[c] Not detected. Detection limit = 0.022 ppm at 7 percent $O_2$.

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outlet $SO_2$ concentrations of 23 and 33 ppm for an average of 28 ppm. $SO_2$ removal efficiency was at 72 percent for both runs. HCl was not detected at the outlet, for a removal efficiency of at least 99.99 percent.

Acid gas data from the FF inlet taken during the October testing are presented in Table 5-13. Three test runs were conducted for each unit. Although not collected simultaneously with the inlet and outlet acid gas samples, when compared to typical inlet values measured previously at St. Croix, the data suggest that 60 to 90 percent $SO_2$ removal occurred across the heat exchanger. For HCl, 85 to 95 percent of the inlet amount was removed across the heat exchanger.

Inlet $SO_2$ concentration appears to affect performance. The highest outlet $SO_2$ concentrations were obtained at inlet $SO_2$ concentrations above 115 ppm. At inlet $SO_2$ emissions below 90 ppm, four of five runs yielded outlet $SO_2$ emissions below 9 ppm. Because the HCl removal was consistently near 100 percent, the effects of stoichiometric ratio, and inlet HCl concentration on performance cannot be evaluated. In Figure 5-4, $SO_2$ removal efficiency is shown as a function of stoichiometric ratio. In general, $SO_2$ removal efficiency increased as stoichiometric ratio increased. Fly ash recirculation does not appear to affect $SO_2$ removal efficiency. Higher $SO_2$ removal efficiencies were obtained at a recirculation ratio of 3.5 than at a ratio of 16.

Particulate data from the May and October test programs are presented in Table 5-14. Outlet PM concentrations ranged from 0.010 to 0.020 gr/dscf at 12 percent $CO_2$. The results from the May tests did not meet the permit requirements for solid plus condensible particulate (not reported here). Minor changes were made to the system prior to the October 1988 testing which lowered the average outlet PM concentrations from 0.015 to 0.012 gr/dscf, as shown by the October results.

Metals data from the June testing are presented in Table 5-15. Three runs were conducted at a FF inlet temperature of 223$^oF$. Low emissions were measured for all the metals. Based on typical uncontrolled metals concentrations (Section 1.2), all metals were removed at greater than

TABLE 5-13. FABRIC FILTER INLET ACID GAS DATA FOR ST. CROIX

| Test Condition | Run Number[a] | FF Inlet Temperature (°F) | Fabric Filter Inlet Acid Gas Concentration (ppm, dry at 7% $O_2$) | |
|---|---|---|---|---|
| | | | $SO_2$ | HCl |
| Combustor = Normal<br>DSI/FF<br>Lime feed = 100 lb/hr<br>No ash recycle | N-1 | NM[b] | 47 | 41 |
| | N-2 | NM | 89 | 34 |
| | N-3 | NM | 14 | 45 |
| Average North | | NM | 50 | 40 |
| | S-1 | NM | 11 | 87 |
| | S-2 | NM | 8.1 | 19 |
| | S-3 | NM | 7.8 | 119 |
| Average South | | NM | 9.0 | 75 |

[a] Heat exchanger identification is given first (N=north, S=south) followed by the run number.

[b] NM = Not measured.

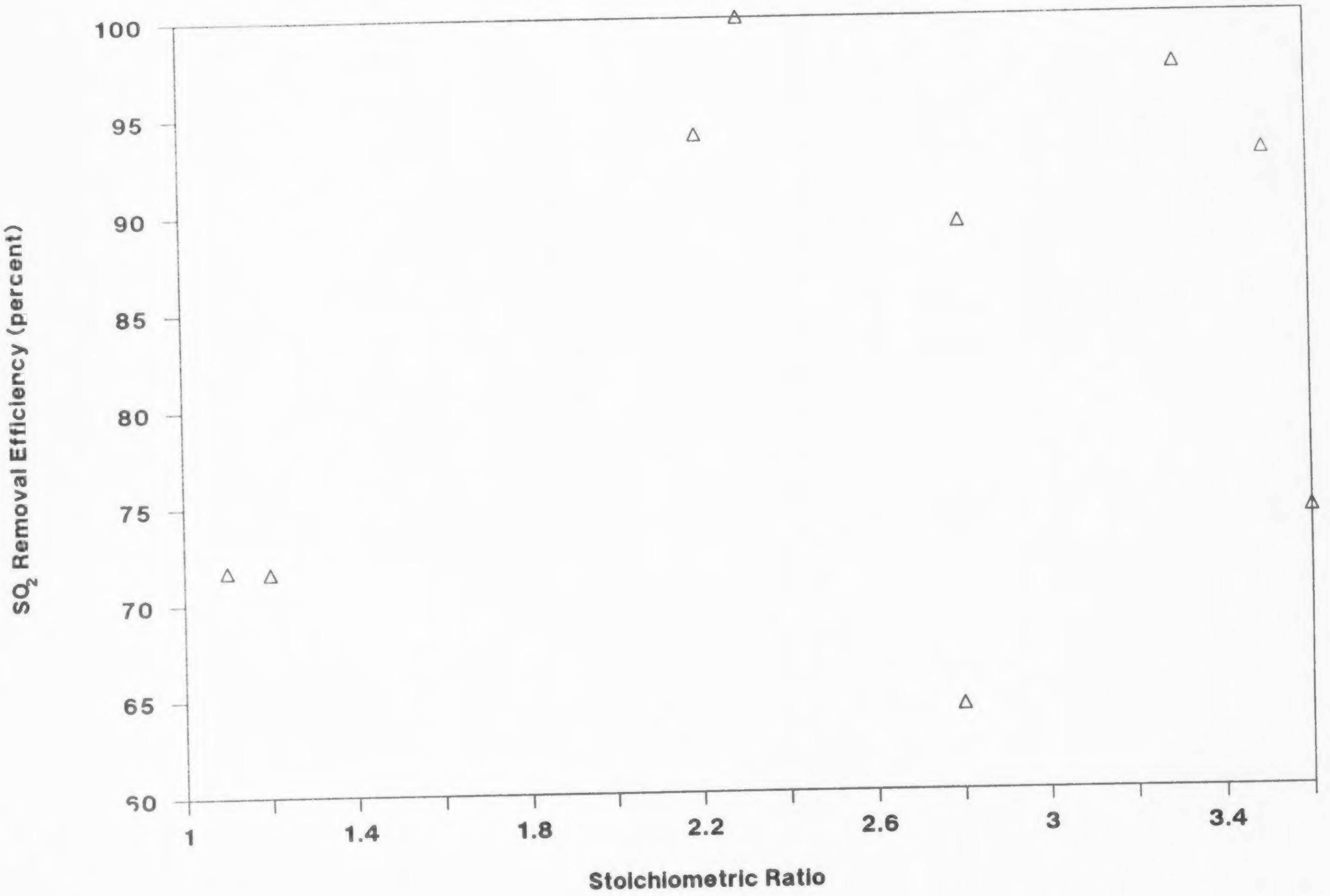

Figure 5-4. $SO_2$ removal efficiency as a function of stoichiometric ratio at the St. Croix DSI/FF system.

## TABLE 5-14. PARTICULATE DATA FOR ST. CROIX

| Test Condition | Run Number | FF Inlet Temperature (°F)[a] | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1 | 220 | 27,200 | 0.011 |
| DSI/FF = Normal | 2 | 220 | 27,500 | 0.012 |
| (6/88 tests) | 3 | 220 | 27,700 | 0.020 |
| Average | | 220 | 27,500 | 0.015 |
| Combustor = Normal | 1 | 227 | 28,900 | 0.010 |
| DSI/FF = Normal | 2 | 227 | 28,900 | 0.011 |
| (10/88 tests) | 3 | 227 | 28,800 | 0.016 |
| Average | | 227 | 28,900 | 0.012 |

[a] Temperature estimated from a measured value at the stack and an assumed temperature drop across the fabric filter (10°F).

## TABLE 5-15. METALS DATA FOR ST. CROIX

| Test Condition | Run Number | FF Inlet Temperature (°F)[a] | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal | 1 | 223 | NM[b] | ND[c] | 3.6 | 55 | 26 | 43 | 52 |
| DSI/FF = Normal | 2 | 223 | NM | ND | 3.2 | 17 | 17 | 39 | 29 |
| (6/88 tests) | 3 | 223 | NM | 6.3 | ND | 7 | 12 | 24 | 14 |
| Average | | 223 | 0.015[d] | 2.1 | 2.3 | 26 | 18 | 35 | 32 |

[a] Temperature estimated from a measured value at the stack and and assumed temperature drop across the fabric filter (10°F).

[b] NM = not measured.

[c] ND = not detected.

[d] Particulate not measured simultaneously with metals. Average result from 6/88 test reported.

94 percent efficiency. Removal efficiencies for cadmium and lead were at least 99 percent. Removal efficiencies for arsenic, nickel, and mercury were 96 to 97 percent. Chromium removal efficiency was 94 percent.

CDD/CDF data are reported in Table 5-16. Outlet CDD/CDF concentrations ranged from 2.8 to 11.8 ng/dscm at 7 percent $O_2$ and averaged 7.7 ng/dscm. Inlet CDD/CDF concentration was not measured.

### 5.2.5 Wurzburg[12]

The MWC facility at Wurzburg, West Germany, consists of two identical mass burn, waterwall combustors with Martin GmbH grates, each designed to combust 330 tons/day of MSW. Flue gas exiting each boiler flows through a water spray quench chamber, after which, powdered hydrated lime is injected into the flue gas in a reactor chamber. Particulate matter is removed by a pulse-jet cleaned fabric filter. The flue gas flow at the FF inlet is typically 50,000 acfm at 375°F. No other information is available on the air pollution control system.

Testing was performed at the facility in January 1986 in order to document emission levels using U.S. EPA test protocols. The combustor and DSI/FF system were operated under normal conditions during testing. At the FF outlet, flue gas was analyzed for $SO_2$, HCl, PM, metals, CDD/CDF, and vinyl chloride.

Acid gas data are presented in Table 5-17. Five test runs were conducted at a FF inlet temperature of 380°F. Outlet $SO_2$ concentrations for the final two runs tested were 145 and 199 ppm at 7 percent $O_2$. Outlet HCl concentrations ranged from 29 to 59 ppm at 7 percent $O_2$ over the five test runs and averaged 45 ppm. The temperature range is too limited to evaluate the effect of temperature on HCl emissions.

In Table 5-18, particulate data for samples collected simultaneously with the HCl samples are presented. The outlet PM concentration ranged from 0.0025 to 0.0074 gr/dscf at 12 percent $CO_2$ over three runs and averaged 0.0042 gr/dscf.

Metals data are presented in Table 5-19. These data represent analysis of particulate collected over 18 hours. Very low concentrations were measured for the metals, suggesting removal efficiencies greater than 99 percent for arsenic, cadmium, chromium, lead, and nickel. Mercury was not measured.

TABLE 5-16. CDD/CDF DATA FOR ST. CROIX

| Test Condition | Run Number | FF Inlet Temperature (°F)[a] | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1 | 223 | 8.61 |
| DSI/FF = Normal | 2 | 220 | 2.80 |
| (6/88 tests) | 3 | 220 | 11.8 |
| Average | | 221 | 7.73 |

[a] Temperature estimated from measured value of the stack and an assumed temperature drop across the fabric filter (10°F).

TABLE 5-17. ACID GAS DATA FOR WURZBURG

| Test Condition | Run Number | FF Inlet Temperature (°F) | Stoichiometric Ratio | Outlet Acid Gas Concentrations (ppmv, dry at 7% $O_2$) | |
|---|---|---|---|---|---|
| | | | | $SO_2$ | HCl |
| Combustor = Normal | 1 | 381 | NM[a] | NM | 29 |
| DSI/FF = Normal | 2 | 382 | NM | NM | 59 |
| | 3 | 365 | NM | NM | 45 |
| | 4 | NM | NM | 145 | 42 |
| | 5 | NM | NM | 199 | 50 |
| Average | | 376 | NM | 172 | 45 |

[a] NM = Not measured.

## TABLE 5-18. PARTICULATE DATA FOR WURZBURG

| Test Condition | Run Number | FF Inlet Temperature (°F) | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1 | 381 | 50,400 | 0.0025 |
| DSI/FF = Normal | 2 | 382 | 48,100 | 0.0074 |
| | 3 | 365 | 51,500 | 0.0026 |
| Average | | 376 | 50,000 | 0.0042 |

## TABLE 5-19. METALS DATA FOR WURZBURG

| Test Condition | Run Number | FF Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Ni |
| Combustor = Normal<br>DSI/FF = Normal<br>(18-hour test) | 1 | 365 | 0.0042 | ND[a] | 5.5 | 0.50 | 11 | 0.23 |

[a] ND = Not Detected

In Table 5-20, CDD/CDF data are presented. Outlet CDD/CDF concentrations ranged from 17.2 to 82.0 ng/dscm over three runs and averaged 40.4 ng/dscm. The average FF inlet temperature was 374°F; however, there was insufficient range in temperature to allow determination of the effect of temperature on performance. No inlet PM or CDD/CDF data were collected, preventing analysis of the effects of these parameters.

## 5.3 SUMMARY OF PERFORMANCE

Section 5.2 discussed DSI/FF performance for individuals systems. This section combines the data from these facilities to examine the relationship between key operating parameters (temperature and stoichiometric ratio) and DSI/FF performance.

### 5.3.1 Acid Gas

Analysis of acid gas data shows that the fabric filter inlet temperature significantly affects $SO_2$ and HCl removal efficiency with DSI/FF systems. As shown in Figures 5-5 and 5-6 for $SO_2$ and HCl, respectively, removal efficiency across the DSI/FF systems increases as temperature decreases for individual facilities as well as for the whole data set. Better than 90 percent $SO_2$ and 95 percent HCl removal efficiency is demonstrated with a DSI/FF system at a FF inlet temperature of 250°F. The data from St. Croix showing 70 to 99 percent $SO_2$ removal efficiency demonstrate the impact of increasing the stoichiometric ratio. At a temperature between 250 and 300°F, the same levels of performance may be achievable with a higher stoichiometric ratio than required at lower temperatures. Several vendors of DSI/FF systems claim that removal efficiencies of 90 percent for $SO_2$ and 95 percent for HCl are readily achievable using DSI/FF systems.[13,14,15]

### 5.3.2 Particulate Matter

Outlet PM concentrations averaged 0.01 gr/dscf or lower at all six of the DSI/FF systems tested.

### 5.3.3 Metals

Metals removal efficiency data are only available for Quebec City. However, based on measured outlet concentrations, removal efficiencies were

## TABLE 5-20. CDD/CDF DATA FOR WURZBURG

| Test Condition | Run Number | FF Inlet Temperature | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal<br>DSI/FF = Normal | 1 | 375 | 82.0 |
| | 2 | 373 | 21.9 |
| | 3 | 373 | 17.2 |
| Average | | 374 | 40.4 |

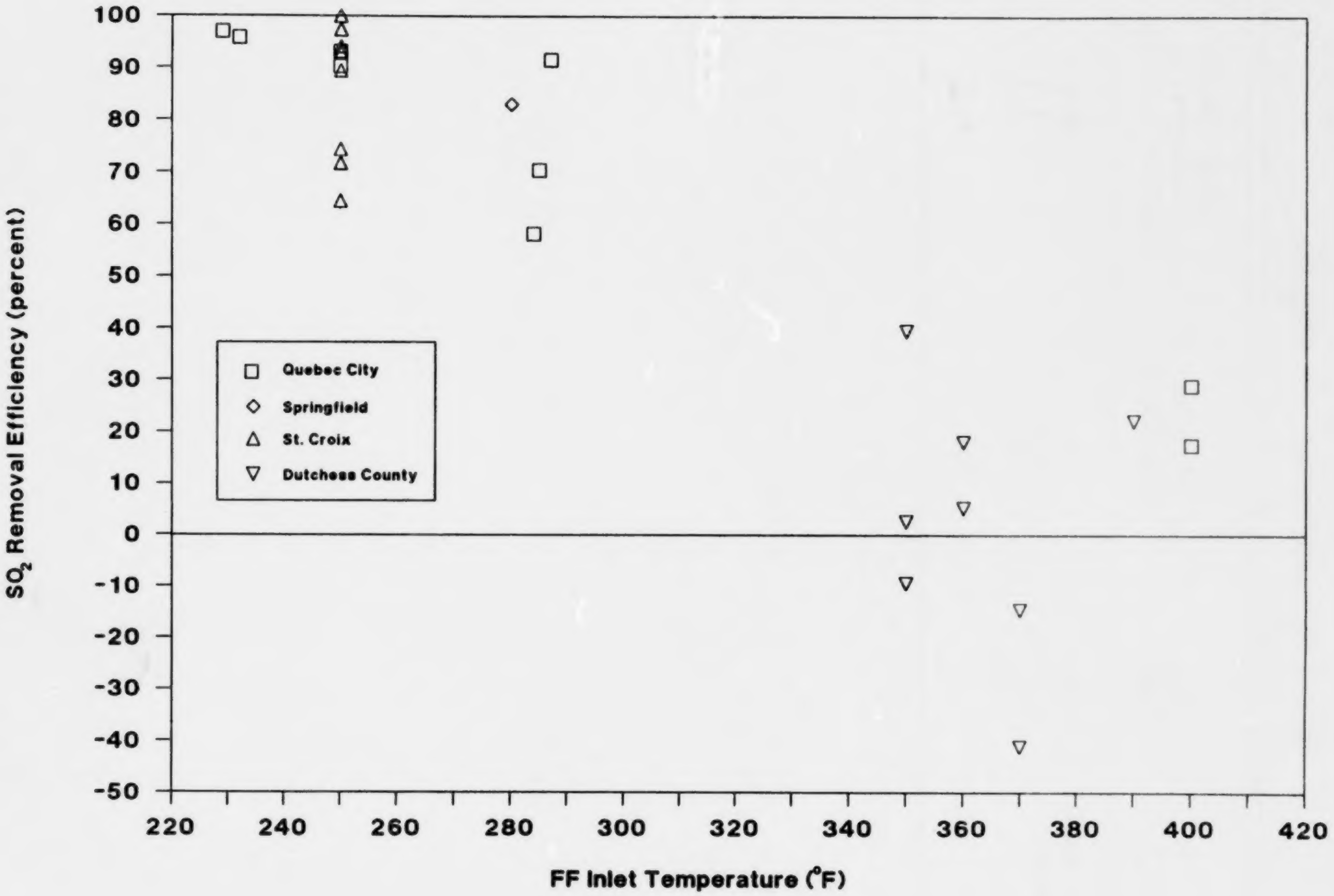

Figure 5-5. SO$_2$ removal efficiency as a function of FF inlet temperature for DSI/FF systems.

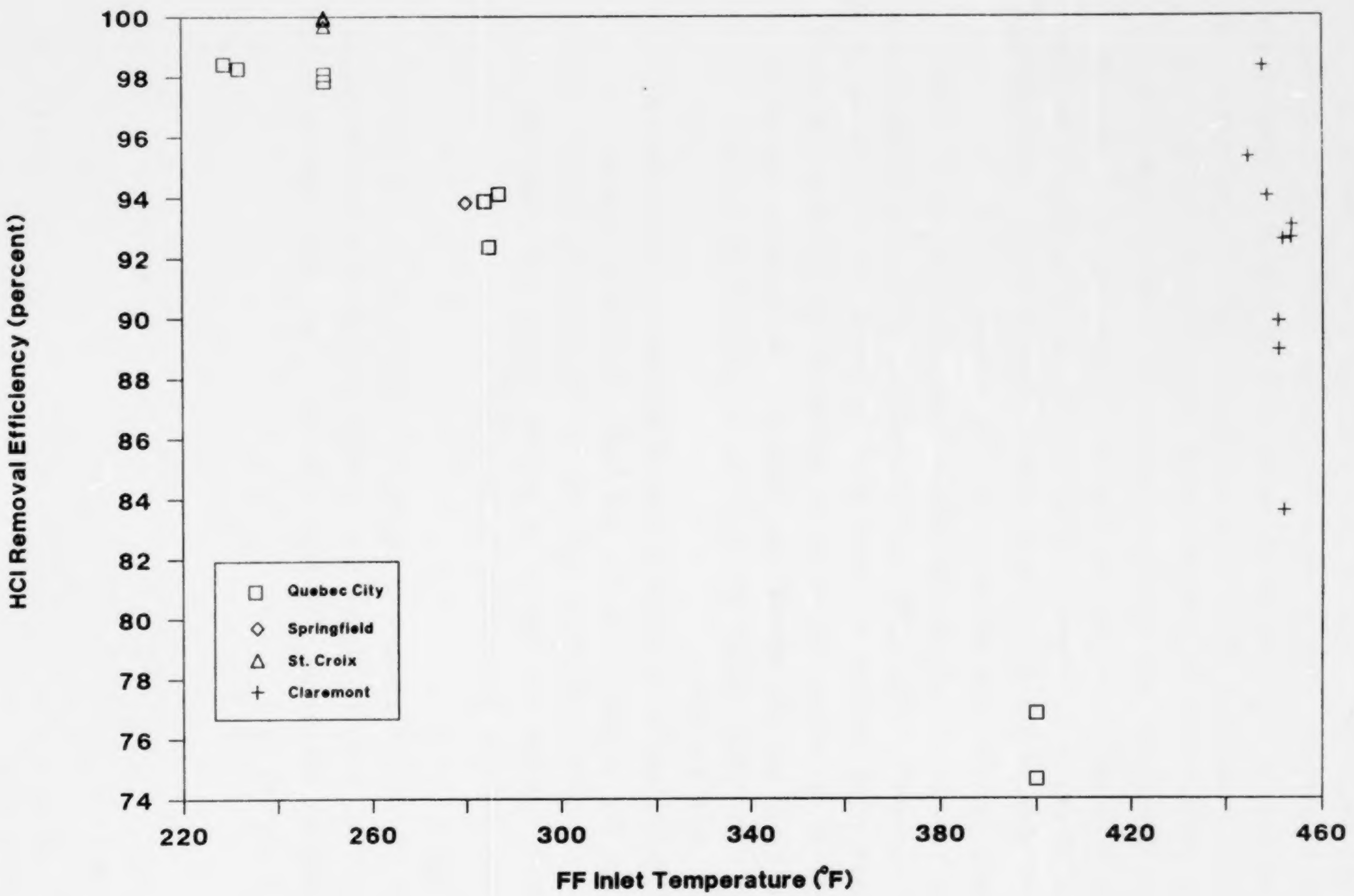

Figure 5-6. HCl removal efficiency as a function of FF inlet temperature for DSI/FF systems.

estimated for the DSI/FF systems at Dutchess County, Springfield, St. Croix and Wurzburg. For cadmium and lead, removal efficiencies were 99 percent or greater at all facilities. Four of five sites had arsenic removal at greater than 99 percent. Two of three runs at the fifth site, St. Croix, had estimated removal efficiencies of better than 99 percent. Chromium and nickel were not removed as effectively as the previously listed metals. At Quebec City, greater than 99 percent removal efficiency was measured for both metals. Similarly, the measured chromium and nickel emissions at Wurzburg and Dutchess County suggest removal efficiencies of at least 99 percent. At Springfield, however, estimated removal efficiencies for both metals are 97 percent and at St. Croix, the estimated removal efficiencies are 94 percent for chromium and 96 percent for nickel.

Mercury removal efficiency depended on temperature at the FF inlet. For systems operating below $300^{0}$F, mercury removal efficiency ranged from a measured value of 99 percent at Quebec City, to estimated efficiencies of 93 to 97 percent at St. Croix, and 40 to 70 percent at Springfield. At $400^{0}$F at Quebec City, no mercury removal was observed. At Dutchess County, at $430^{0}$ and $365^{0}$F, mercury removal efficiencies of zero and 80 percent, respectively, were estimated.

Removal efficiencies of greater than 99 percent are achievable by DSI/FF systems for arsenic, cadmium, and lead. Similarly, removal efficiencies of 96 percent can be achieved for chromium and nickel. For mercury, DSI/FF systems can achieve 70 percent removal efficiency by decreasing the FF inlet temperature to below $300^{0}$F.

### 5.3.4 CDD/CDF

Removal of CDD/CDF appears to depend on temperature at the fabric filter inlet. As shown in Figure 5-7, average CDD/CDF emissions decreased as the temperature decreased. At less than $300^{0}$F, emissions were below 7.7 ng/dscm at 7 percent $O_2$.

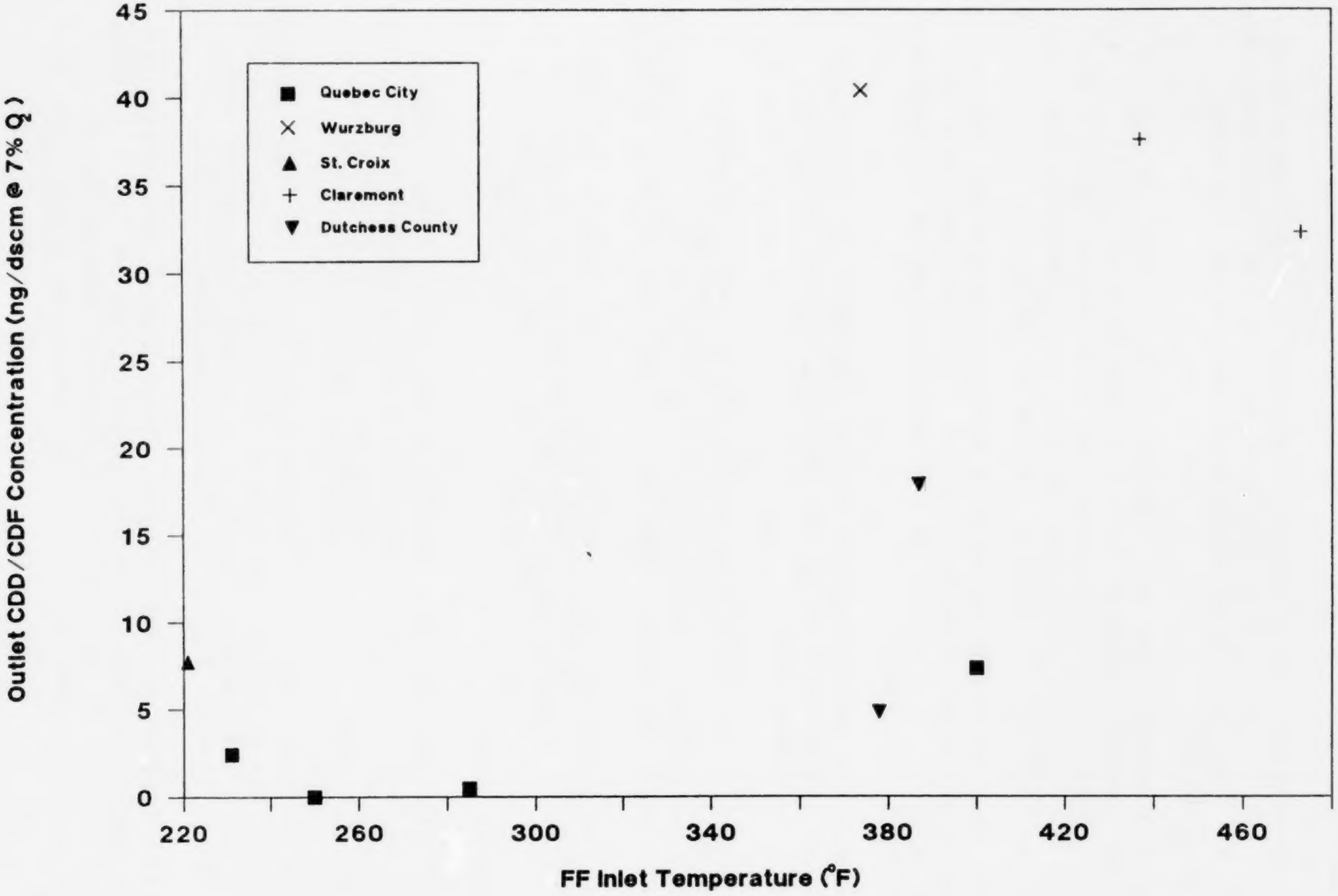

Figure 5-7. Outlet CDD/CDF concentration as a function of FF inlet temperature for DSI/FF systems.

## 5.4 REFERENCES

1. Municipal Waste Combustion Study, Flue Gas Cleaning Technology. U. S. Environmental Protection Agency. EPA/530-SW-87-021d. pp. 2-17.

2. Almega Corporation. SES Claremont, Claremont, NH, NH/VT Solid Waste Facility. Unit 1 and Unit 2, EPA Stack Emission Compliance Tests, May 26, 27, and 29, 1987. Prepared for Clark-Kenith, Inc. Atlanta, Georgia. July 1987.

3. Entropy Environmentalists, Inc. Stationary Source Sampling Report, Signal Environmental Systems, Inc., Claremont Facility, Claremont, New Hampshire, Dioxins/Furans Emissions Compliance Testing, Units 1 and 2. Prepared for Signal Environmental Systems, Inc., Claremont, New Hampshire. Reference No. 5553-A. October 2, 1987.

4. Beachler, D.S. (Westinghouse Electric Corporation) and ETS, Inc. Dutchess County Resource Recovery Facility Emission Compliance Test Report, Volumes 1-5. Prepared for New York Department of Environmental Conservation. June 1989.

5. Flakt Canada Ltd. and Environment Canada. The National Incinerator Testing and Evaluation Program, Air Pollution Control Technology, Volume 4. September 1986.

6. McClanahan, D (Fluor Daniel), A. Licata (Dravo), and J Buschmann (Flakt, Inc.). Operating Experience with Three APC Designs on Municipal Incinerators. Proceedings of the International Conference on Municipal Waste Combustion. April 11-14, 1988. pp. 7C-19 to 7C-41.

7. Interpoll Laboratories, Inc. Results of the June 1988 Air Emission Performance Test on the MSW Incinerators at the St. Croix Waste to Energy Facility in New Richmond, Wisconsin. Prepared for American Resource Recovery. Waukesha, Wisconsin. Report No. 8-2560. September 12, 1988.

8. Interpoll Laboratories, Inc. Results of the June 6, 1988, Scrubber Performance Test at the St. Croix Waste to Energy Incineration Facility in New Richmond, Wisconsin. Prepared for Interel Corporation. Englewood, Colorado. Report No. 8-2560I. September 20, 1988.

9. Interpoll Laboratories, Inc. Results of the August 23, 1988, Scrubber Performance Test at the St. Croix Waste to Energy Incineration Facility in New Richmond, Wisconsin. Prepared for Interel Corporation. Englewood, Cololrado. Report No. 8-2609. September 20, 1988.

10. Interpoll Laboratories, Inc. Results of the October 1988 Particulate Emission Compliance Test on the MSW Incinerator at the St. Croix Waste to Energy Facility in New Richmond, Wisconsin. Prepared for American Resource Recovery. Waukesha, Wisconsin. Report No. 8-2547. November 3, 1988.

11. Interpoll Laboratories, Inc. Results of the October 21, 1988, Scrubber Performance Test at the St. Croix Waste to Energy Facility in New Richmond, Wisconsin. Prepared for Interel Corporation. Englewood, Colorado. Report No. 8-2648. December 2, 1938.

12. Hahn, J. L. (Cooper Engineers, Inc.). Air Emissions Testing at the Martin GmbH Waste-to-Energy Facility in Wurzburg, West Germany. Prepared for Ogden Martin Systems, Inc. Paramus, New Jersey. January 1986.

13. Telecon. D. M. White, Radian Corporation, with J. Buschmann, Flakt, Inc. June 8, 1989. Subject: Achievable acid gas reductions and retrofit times.

14. Meeting Presentation. R. Ireland, Procedair Industries, with Industrial Studies Branch, Office of Air Quality Planning and Standards. March 30, 1989. Subject: Performance of Dry Injection/ Fabric Filter Systems.

15. Meeting Presentation. E. B. Mull, Interel Corporation, with Industrial Studies Branch, Office of Air Quality Planning and Standards. April 1989.

# 6.0 SPRAY DRYING FOLLOWED BY AN ELECTROSTATIC PRECIPITATOR

Section 6.0 describes the technology and performance of spray dryer systems followed by an ESP. In Section 6.1, SD/ESP operation and design is described. In Section 6.2, descriptions of facilities with emissions data for SD/ESP systems and summaries of the available data from each facility are provided. In Section 6.3, the performance of SD/ESP systems at controlling acid gas, PM, metals, and CDD/CDF emissions is discussed.

## 6.1 PROCESS DESCRIPTION

Spray drying is designed to control acid gases, but also provides control of organics and volatile metal emissions from MWC's. In the spray drying process, lime slurry is injected into the spray dryer (SD) chamber through either a rotary atomizer or two-fluid nozzles. Rotary atomizers use centrifugal energy to atomize the slurry. The slurry is fed to the center of a rapidly rotating disk or wheel where it flows outward to the edge of the disk. The slurry is atomized as it leaves the surface of the rapidly rotating disk. Two-fluid nozzles use kinetic energy to atomize the slurry. High velocity air is injected into a stream of slurry, breaking the slurry into droplets, which are ejected at near-sonic velocities into the spray drying chamber. Both of these atomization methods have been used in spray dryers on MWC's. Spray dryers with two-fluid nozzles are typically larger in height than diameter while those with rotary atomizers have a larger diameter than height. Slurry droplets of comparable size can be obtained with both two-fluid nozzles and rotary atomizers, minimizing differences in performance due to atomizer type.[1]

The atomized slurry droplets contact the hot flue gas in the SD chamber. The moisture in the lime slurry evaporates to cool the flue gas, and the lime reacts with the acid gases in the flue gas to form calcium salts. The SD chamber is designed to provide sufficient contact and residence time to produce a dry product leaving the SD chamber. The residence time in the chamber is typically 10 to 15 seconds. The particulate exiting the SD contains fly ash plus calcium salts, water, and unreacted lime. The simultaneous evaporation and reaction in the spray drying process increases the moisture and particulate content of the flue gas.

Key design and operating parameters that can significantly affect SD performance are SD outlet temperature, lime-to-acid gas stoichiometric ratio, and slurry droplet size. The SD outlet temperature is controlled by the amount of water in the slurry. More effective acid gas removal occurs at lower temperatures, but the temperature must be kept high enough to ensure the slurry and reaction products are adequately dried prior to collection in the ESP. In addition, a minimum SD outlet temperature of approximately 240°F is required to control agglomeration of PM and sorbent by calcium chloride.[2]

The stoichiometric ratio is defined as the molar ratio of calcium in the lime slurry fed to the SD to the theoretical amount of calcium required to completely react with the HCl and $SO_2$ in the flue gas at the inlet to the SD. At a ratio of 1.0, the moles of calcium are equal to the moles of incoming HCl and $SO_2$. However, because of mass transfer limitations, incomplete mixing, differing rates of reaction ($SO_2$ reacts more slowly than HCl), and the presence of other acid gases that react with calcium (e.g. hydrogen fluoride, sulfur trioxide), more than the theoretical amount of lime is generally fed to the spray dryer. Although not usually measured during a compliance test, droplet size would be expected to affect SD performance. Smaller droplet size increases the surface area for reaction between lime and acid gases and increases the rate of water evaporation.

The amount of lime fed is generally controlled by one of two means. In one approach, the lime slurry feed rate is controlled by an acid gas analyzer/controller (generally based on $SO_2$) at the stack. As the outlet acid gas concentration increases or decreases, the lime slurry feed rate is accordingly raised or lowered, respectively, to maintain a specified outlet acid gas concentration. The second approach uses a constant lime slurry feed rate that is sufficient to react with peak expected acid gas concentrations. Both systems are currently in use, although the system using an analyzer/controller is more frequently encountered.

There are no significant mechanical or electrical differences between ESP's downstream of SD or ESP's used alone. The PM control performance of both is affected by the number of ESP fields, specific collection area, and particle size, resistivity, and migration velocity as discussed in Section 2.0. Operating temperatures of ESP's installed following a SD are generally between 250 and 300°F, versus 350°F and above for conventional, stand-alone ESP's. A heavy rapper system is employed with an ESP downstream of a SD because the PM adheres more strongly to ESP surfaces due to the calcium chloride content.

## 6.2 SUMMARY OF TEST DATA

Section 6.2 presents the available emission data for MWC facilities with SD/ESP systems. A description of each facility and a summary and analysis of the emission data are provided for each facility. All of the data presented in this section are based on short-term compliance testing (generally several hours per run). A review of longer-term performance data for acid gases from the Millbury MWC is presented in Appendix A.

### 6.2.1 Millbury[3,4,5]

The Millbury Resource Recovery Facility in Millbury, Massachusetts, consists of two identical mass burn combustor trains, each designed to combust 750 tons per day of municipal solid waste (MSW). The MSW is combusted on a Von Roll reciprocating inclined grate in a Babcock and Wilcox waterwall combustor. Each boiler is rated to produce 190,000 lbs per hour of superheated steam.

The combustion gases exiting the combustor enter a spray dryer/ESP emission control system designed by Wheelabrator Air Pollution Control Systems. Slaked lime, along with metered dilution water is injected into the spray dryer vessel through two-fluid nozzles. The system is designed to independently control the lime and dilution water feed rates. The lime slurry feed rate is varied automatically to maintain a prescribed outlet $SO_2$ concentration. Manual adjustments of the set point are made to control $SO_2$ excursions. Dilution water is added to the lime slurry to reduce the flue gas temperature, which is typically maintained at about 255°F.

The dry solids from the SD and fly ash are collected in a 3-field ESP. The specific collection area of the ESP is 330 $ft^2$ per 1,000 acfm at a flue gas flow of about 160,000 acfm. Each ESP field is cleaned according to a programmed mechanical rapping cycle.

In February 1988, emissions testing was performed by Rust International Corporation to demonstrate compliance with permit conditions and by EPA to assess performance of the SD/ESP on CDD/CDF. During the compliance testing, the combustor and SD/ESP were operated normally. Flue gas at the SD/ESP inlet and outlet of both units was analyzed for $SO_2$ and HCl by manual methods. At both SD/ESP outlets, flue gas samples were analyzed for PM, metals (beryllium, lead, mercury, antimony, arsenic, cadmium, chromium, copper, manganese, molybdenum, nickel, selenium, tin, titanium, vanadium, and zinc), hydrogen flouride, $NO_x$, sulfuric acid mist, non-methane hydrocarbons, reduced sulfur compounds, vinyl chloride, and volatile organic compounds. Generally, these runs were conducted at each unit. CDD/CDF was measured for six runs at the outlet of Unit 2 only. The EPA-sponsored testing consisted of five sampling runs for CDD/CDF at the inlet to the SD/ESP of Unit 2 conducted simultaneously with outlet compliance testing for CDD/CDF.

Acid gas data for Millbury are presented in Table 6-1. Long-term CEM measurements of acid gases are described in Appendix A. The first five runs in the table are from plant CEM data during CDD/CDF sampling. The plant CEM's were not certified at the time of this testing, however, and the $SO_2$ data and stoichiometric ratios are shown for comparison only. The remainder of the data, three runs for each unit, were collected using manual methods as part of the compliance test. Outlet $SO_2$ concentrations during the six compliance test runs ranged from 41 to 75 ppmv at 7 percent $O_2$. The average outlet $SO_2$ concentration from Unit 1 was 23 ppm and the average outlet $SO_2$ concentration from Unit 2 was 62 ppm. The corresponding $SO_2$ removal efficiencies for Units 1 and 2 averaged 73 and 79 percent, respectively. Concentrations of HCl at the ESP outlet ranged from 4.1 to 31 ppm at 7 percent $O_2$. The average outlet HCl concentration from Unit 1 was 23 ppm and the average outlet HCl concentration from Unit 2 was 6 ppm. The corresponding HCl removal efficiencies were 97 and 99 percent, respectively, for Units 1 and 2. Removal efficiencies for $SO_2$ and HCl for Unit 2 are higher than for Unit 1. This may be due to the difference in ESP

TABLE 6-1. ACID GAS DATA FOR MILLBURY

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F) | Stoichiometric Ratio | Acid Gas Concentration (ppmv, dry at 7% $O_2$) |  |  |  | Acid Gas Removal Efficiency (%) |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | Inlet |  | Outlet |  |  |  |
|  |  |  |  | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl |
| Combustor = Normal | 2-1 | 255 | 1.3[b] | 108[c] | NM[d] | 17.1[c] | NM | 83.5[e] | -- |
| SD/ESP = Normal | 2-2 | 255 | 1.2[b] | 95[c] | NM | 17.8[c] | NM | 81.5[e] | -- |
|  | 2-3 | 255 | 1.6[b] | 236[c] | NM | 44.6[c] | NM | 80.7[e] | -- |
|  | 2-4 | 253 | 1.4[b] | 215[c] | NM | 47.6[c] | NM | 76.8[e] | -- |
|  | 2-5 | 250 | 0.85[b] | 216[c] | NM | 42.0[c] | NM | 78.8[e] | -- |
| Average (Unit 2 - CDD/CDF tests) |  | 254 | 1.3[b] | 174[c] | NM | 33.8[c] | NM | 80.3[d] | -- |
|  | 1-1 | 251 | NA[f] | 138 | 847 | 45.6 | 7.67 | 67.0 | 99.1 |
|  | 1-2 | 252 | NA | 274 | 697 | 74.9 | 31.3 | 72.7 | 95.5 |
|  | 1-3 | 253 | NA | 204 | 767 | 41.2 | 31.0 | 79.9 | 96.0 |
| Average (Unit 1) |  | 252 | NA | 205 | 770 | 53.9 | 23.3 | 73.2 | 96.9 |
|  | 2-1 | 243 | NA | 318 | 794 | 59.0 | 9.73 | 81.5 | 98.8 |
|  | 2-2 | 243 | NA | 254 | 704 | 52.1 | 4.40 | 79.5 | 99.4 |
|  | 2-3 | 244 | NA | 315 | 593 | 73.4 | 4.11 | 76.7 | 99.3 |
| Average (Unit 2) |  | 243 | NA | 296 | 697 | 61.5 | 6.08 | 79.2 | 99.2 |

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[a] Run Number consists of unit number followed by the run number on that unit.

[b] Stoichiometric ratio estimated based on measured lime feedrate and continuous $SO_2$ levels and average inlet HCl concentration from compliance tests.

[c] $SO_2$ concentration in ppmv, as measured from plant CEM data on Unit 2. Plant CEM's were not certified at the time of the test. The $O_2$ data collected for these runs were on a wet basis and are not used to normalize the data.

[d] NM = Not Measured.

[e] Removal efficiency calculated based on as-measured concentration (not included in overall average).

[f] NA = Not Available. Lime feed rate was not measured.

inlet temperature (243°F for Unit 2 versus 252°F for Unit 1). However, due to the lack of data on stoichiometric ratio, atomization quality, and other factors such as relative mixing, the cause of this difference in performance cannot be evaluated in more depth.

As shown in Figure 6-1, outlet $SO_2$ and HCl emissions increased with increasing inlet $SO_2$ concentration during testing. Both $SO_2$ and HCl removal efficiencies appear relatively independent of inlet $SO_2$ concentration. There is no apparent affect of inlet HCl concentration on outlet $SO_2$ or HCl emissions. The SD/ESP system at Millbury demonstrated better than 70 percent $SO_2$ removal efficiency and 95 percent HCl removal efficiency at an ESP operating temperature of 250°F.

The particulate data for Millbury are presented in Table 6-2. Outlet PM concentrations from three runs at both units ranged from 0.0014 to 0.019 gr/dscf at 12 percent $CO_2$. The average PM outlet concentration was 0.0018 gr/dscf for Unit 1 and 0.0083 gr/dscf for Unit 2. Thus, although the use of spray drying increases PM loading to the ESP, the 3-field ESP at Millbury operating at 225°F with an SCA of approximately 330 $ft^2$/1,000 acfm yielded outlet PM levels below 0.01 gr/dscf for five of six runs.

Table 6-3 presents the metals emissions data from three runs at each unit (six Mercury runs at Unit 1). Metal emissions were similar at both units. Outlet arsenic concentrations averaged 3.6 and 4.6 ug/dscm. Cadmium and nickel emissions were similar, at 15 to 20 ug/dscm. Outlet chromium emissions averaged 48 and 98 ug/dscm and lead emissions were about 300 ug/dscm. Compared to typical uncontrolled metals concentrations (Section 1.2), removal efficiencies for arsenic, cadmium, nickel, and lead were 98 to 99 percent. Chromium was removed at an efficiency of 95 percent. The average mercury emissions of 570 ug/dscm at Unit 1 and 950 ug/dscm at Unit 2 were similar to typical uncontrolled mercury levels, which can range from 250 to 1,000 ug/dscm, suggesting that mercury was not removed by the SD/ESP system.

The CDD/CDF data from Millbury Unit 2 are presented in Table 6-4. Outlet CDD/CDF concentrations ranged from 40 to 103 ng/dscm at 7 percent $O_2$ over six runs and averaged 59 ng/dscm. Five of the six runs were between 40

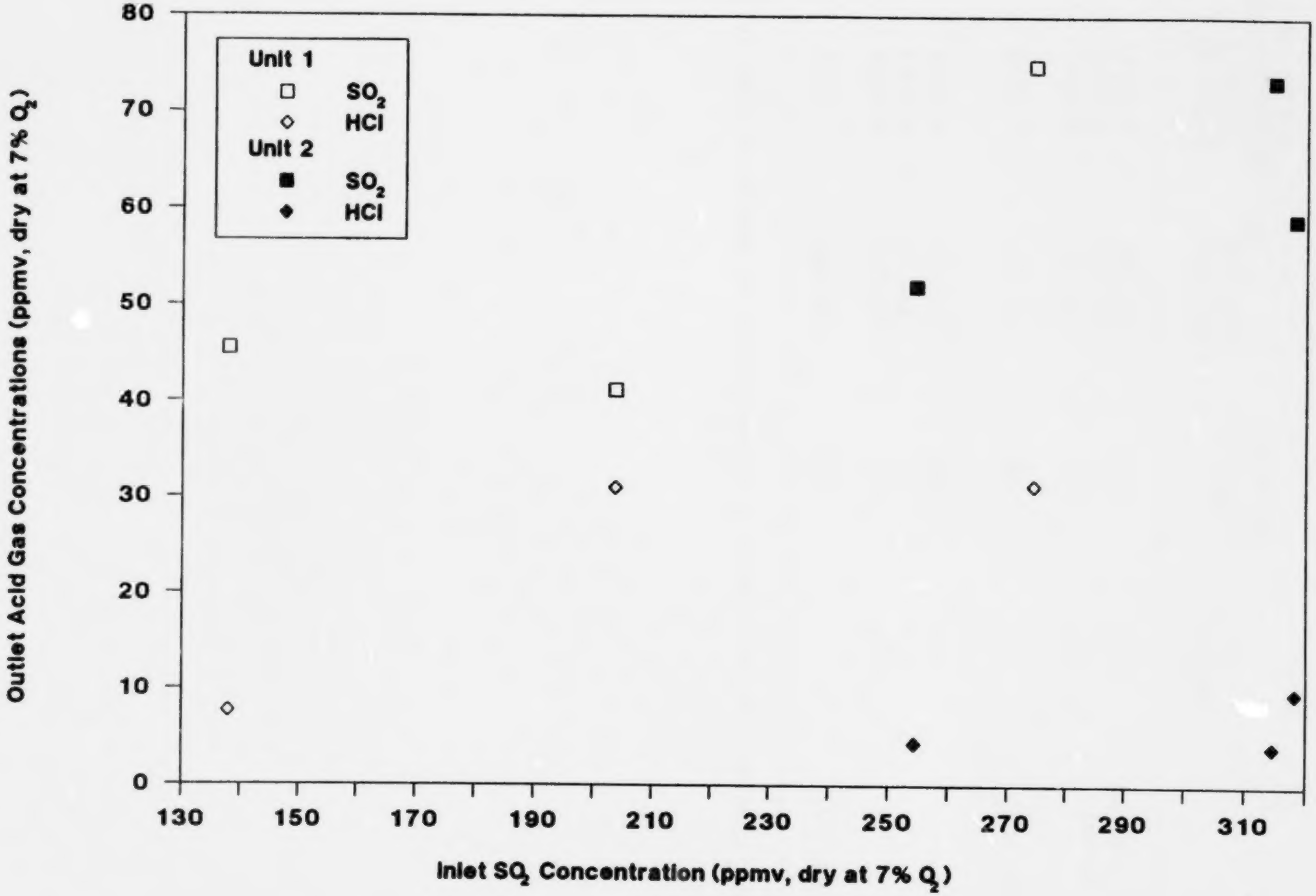

Figure 6-1. Outlet $SO_2$ and HCl concentrations as a function of inlet $SO_2$ concentration at Millbury.

## TABLE 6-2. PARTICULATE DATA FOR MILLBURY

| Condition | Run Number[a] | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1-1 | 254 | 167,540 | 0.0026 |
| SD/ESP = Normal | 1-2 | 256 | 163,280 | 0.0014 |
| | 1-3 | 255 | 154,100 | 0.0015 |
| Average (Unit 1) | | 255 | 161,640 | 0.0018 |
| | 2-1 | 240 | 155,560 | 0.0194 |
| | 2-2 | 240 | 168,540 | 0.0029 |
| | 2-3 | 240 | 163,510 | 0.0025 |
| Average (Unit 2) | | 240 | 162,540 | 0.0083 |

[a] Run Number consists of unit number followed by the run number on that unit.

## TABLE 6-3 METALS EMISSIONS DATA FOR MILLBURY

| Test Condition | Run[a] Number | ESP Inlet Temperature ($^oF$) | Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg[b] | Ni |
| Combustor = Normal<br>SD/ESP = Normal | 1-1 | 254 | 0.0026 | 3.45 | 16.5 | 281 | 231 | 467 | 58.8 |
| | 1-2 | 256 | 0.0014 | 4.03 | 21.2 | 8.9 | 341 | 606 | 7.0 |
| | 1-3 | 255 | 0.0015 | 3.18 | 15.4 | 6.1 | 261 | 709 | ND[c] |
| | 1-4 | 244 | NM[d] | NM | NM | NM | NM | 426 | NM |
| | 1-5 | 243 | NM | NM | NM | NM | NM | 641 | NM |
| | 1-6 | 243 | NW | NM | NM | NM | NM | 542 | NM |
| Average (Unit 1) | | 249 | 0.0018 | 3.55 | 17.7 | 98.7 | 278 | 565 | 21.9 |
| | 2-1 | 240 | 0.019 | 8.86 | 41.0 | 119 | 714 | 947 | 43.3 |
| | 2-2 | 240 | 0.0029 | 2.23 | 12.3 | 11.8 | 144 | 906 | ND |
| | 2-3 | 240 | 0.0025 | 2.70 | 11.2 | 12.4 | 133 | 1,009 | ND |
| Average (Unit 2) | | 240 | 0.0083 | 4.60 | 21.5 | 47.7 | 330 | 954 | 14.4 |

[a] Run Number consists of unit number followed by the run number on that unit.

[b] Mercury emissions for Unit 1 measured in May 1988. Unit 2 and other metals results from February 1988 test.

[c] ND = Not detected. Considered as zero when calculating averages.

[d] NM = Not measured.

## TABLE 6-4. CDD/CDF DATA FOR MILLBURY

| Test Conditions | Run Number[a] | ESP Inlet Temperature | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (%) |
|---|---|---|---|---|---|
| Combustor = Normal | | | | | |
| SD/ESP = Normal | 2-1 | 255 | 210 | 103 | 51.1 |
| | 2-2 | 255 | 202 | 58.2 | 71.3 |
| | 2-3 | 255 | 136 | 51.4 | 62.3 |
| | 2-4 | 253 | 160 | 55.3 | 65.4 |
| | 2-5 | 250 | 140 | 40.4 | 71.3 |
| | 2-6 | 250 | NM[b] | 46.6 | - |
| Average | | 253 | 170 | 59.2 | 64.3 |

[a] Run Number consists of unit number followed by the run number on that unit.

[b] NM = not measured.

and 58 ng/dscm, with the sixth run at 103 ng/dscm. Inlet CDD/CDF concentrations ranged from 136 to 210 ng/dscm at 7 percent $O_2$ for five runs and averaged 170 ng/dscm. Removal efficiencies were between 51 and 71 percent and averaged 64 percent. The range in ESP inlet temperature during the six test runs was from 250 to 255°F. Thus, the SD/ESP system at Millbury, operating at an ESP inlet temperature of 250°F with highly efficient PM and gas control, has demonstrated the capability to reduce moderate inlet CDD/CDF levels by greater than 60 percent.

### 6.2.2 Munich[6]

The Munich North III MWC facility consists of two mass burn combustors each designed to burn 530 tons/day of municipal waste and 288 tons/day of clarified sludge. The emission control system consists of independent Deutsche Babcock Anlagen (DBA) SD/ESP systems for each combustor. The lower inlet section of the SD is a cyclonic preseparator where approximately 50 to 70 percent of the fly ash is removed from the flue gas. From the preseparator section, the flue gas flows upward through the SD where two-fluid nozzles spray lime slurry into the gas stream. The lime feed rate and amount of dilution water for the slurry are adjusted by controllers based on the outlet HCl concentration and SD outlet temperature, respectively. Flue gas from the SD is routed through a 2-field rigid-frame ESP at a flow of approximately 147,000 acfm at 300°F. The SCA of the ESP is unavailable. The ESP exhaust is routed through an ID fan and a concrete stack.

A test program was conducted at the Munich North facility in May 1984 to demonstrate the ability of the SD/ESP system to control pollutants to levels acceptable in the U.S. at that time. Target emission levels of 0.02 gr/dscf for PM, 30 to 100 ppm or 70 percent removal for $SO_2$, and 30 to 50 ppm or 90 percent removal for HCl were established, based on regulations in existence for California, New Jersey, and Connecticut. During these tests, only MSW was fired. The SD outlet temperature and the set point for the outlet HCl concentration were varied during the tests. Flue gas at the SD/ESP inlet and outlet was analyzed for PM, HCl, and $SO_2$. Sampling was also conducted at the SD/ESP outlet for selected metals including arsenic, beryllium, cadmium, chromium, lead, and nickel.

Acid gas data for four test runs at Munich are presented in Table 6-5. Outlet $SO_2$ concentrations ranged from 13 ppm at 7 percent $O_2$ at an ESP inlet temperature of $300^oF$ to 37 ppm at a temperature of $330^oF$. The $SO_2$ removal efficiency was 88 percent at $300^oF$ and about 70 percent for the two runs at $330^oF$. The $SO_2$ removal efficiency could not be evaluated for Run 5 at an ESP inlet temperature of $314^oF$. Outlet HCl concentrations ranged from 4.9 ppm at 7 percent $O_2$ at an ESP inlet temperature of $300^oF$ to 44 ppm at a temperature of $330^oF$. The HCl removal efficiency was 99 percent at an ESP inlet temperature of $300^oF$ and about 94 percent at $300^oF$. HCl removal efficiency could not be evaluated for Run 5 at $314^oF$.

Figure 6-2 presents a plot of $SO_2$ and HCl removal efficiency as a function of stoichiometric ratio. As the ratio varied from a low of 0.89 at an ESP inlet temperature of $330^oF$ to a high of 2.1 at $300^oF$, both $SO_2$ and HCl removal efficiency increased. As shown in Figure 6-3, a plot of $SO_2$ and HCl removal efficiency as a function of ESP inlet temperature, decreasing the temperature also increased performance. However, increasing stoichiometric ratio corresponded with decreasing temperature and as a result, the highest removal efficiency was observed for both $SO_2$ and HCl for Run 2, which had the lowest temperature ($300^oF$) and the highest stoichiometric ratio (2.1). There were no observable effects of inlet acid gas concentration on outlet acid gas concentration or removal efficiency.

Particulate data from the four runs at Munich are presented in Table 6-6. Outlet PM concentrations ranged from 0.0065 to 0.018 gr/dscf at 12 percent $CO_2$. The average PM concentration for all four runs was 0.010 gr/dscf with removal efficiencies exceeding 99 percent. There is no apparent effect of increased inlet PM from the SD or changes in the lime feed rate on the PM control performance of the ESP. There was no observable effect on PM performance due to ESP inlet temperature changes, either.

Outlet metals concentrations are presented in Table 6-7. These data are from a particulate sizing sample collected continuously over 40 hours. Because combustor and ESP operating conditions varied over that period, these data should be considered as worst-case only. Based on typical uncontrolled metals concentrations, arsenic and lead were removed at greater than 99 percent efficiency. Cadmium was removed at 98.6 percent efficiency.

## TABLE 6-5. ACID GAS DATA FOR MUNICH

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Stoichiometric Ratio | Acid Gas Concentration (ppmv, dry at 7% $O_2$) | | | | Acid Gas Removal Efficiency (%) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Inlet | | Outlet | | | |
| | | | | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl |
| Combustor = Normal SD/ESP = Very low SD outlet temperature (266°F) | 2 | 300 | 2.1 | 105 | 588 | 12.8 | 4.9 | 87.8 | 99.2 |
| Combustor = Normal SD/ESP = Low SD outlet temperature (293°F) | 3 | 330 | 1.6 | 52 | 622 | 14.7 | 34.3 | 71.5 | 94.5 |
| | 4 | 330 | 0.9 | 123 | 656 | 36.5 | 44.1 | 70.4 | 93.3 |
| Average | | 330 | 1.2 | 87 | 639 | 25.6 | 39.2 | 71.0 | 93.9 |
| Combustor = Normal SD/ESP = Normal (320°F)[c] | 5 | 314 | NR[d] | NR[d] | NR[d] | 20.4 | 24.3 | -- | -- |

[a] Constant lime slurry feed rate.

[b] Outlet HCl analyzer/controller used to control lime slurry feed rate. Outlet HCl controller set to achieve 30 mg/Nm$^3$, wet, at 11 percent $O_2$ (approximately 32 ppmv, dry, at 7 percent $O_2$)

[c] Outlet HCl analyzer/controller used to control lime slurry feed rate. Outlet HCl controller set to achieve 15 mg/Nm$^3$, wet, at 11 percent $O_2$ (approximately 16 ppmv, dry, at 7 percent $O_2$).

[d] NR = Not reported. Oxygen data unavailable to correct values to 7 percent $O_2$. Flue gas flow rate unknown, preventing calculation of stoichiometric ratio.

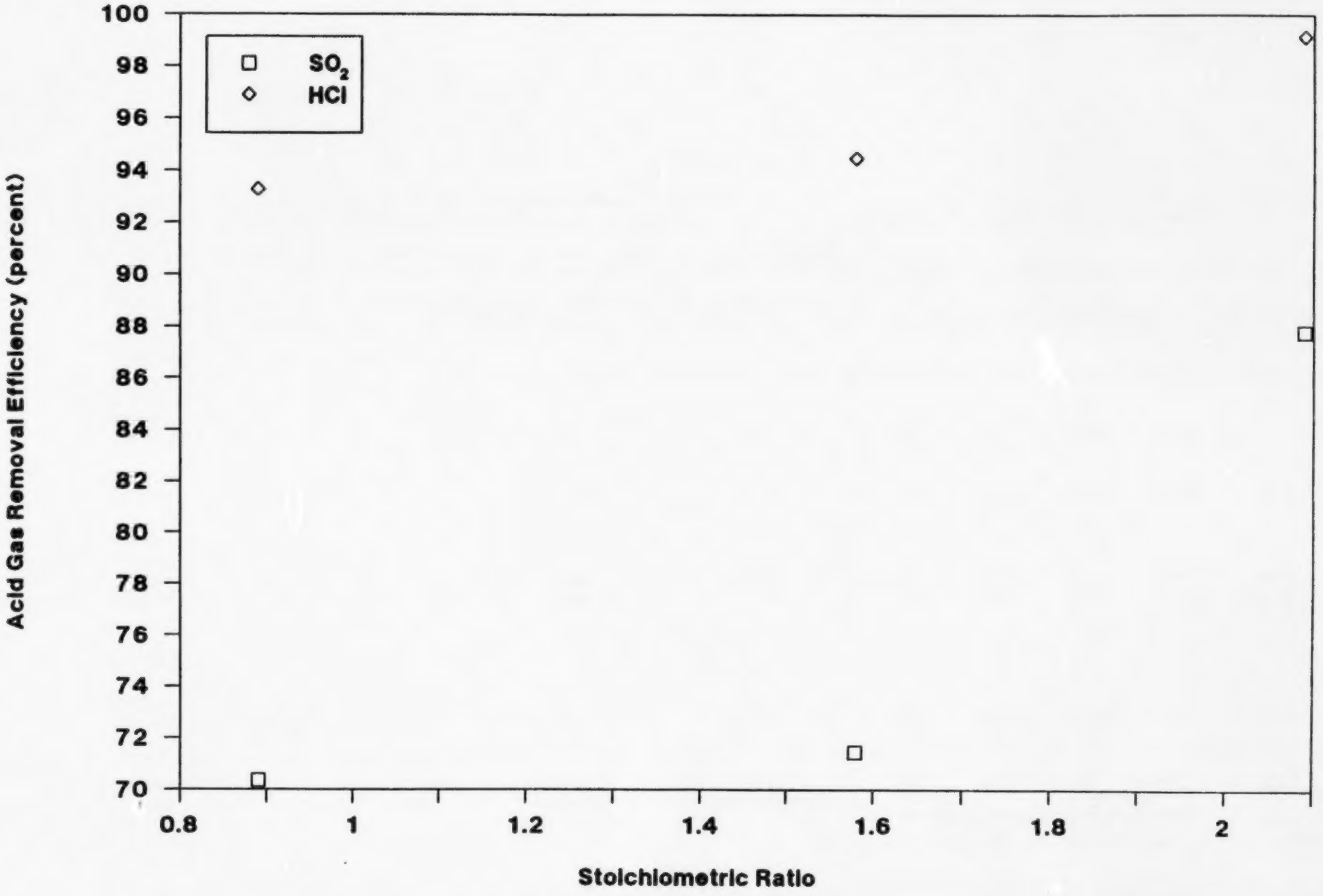

Figure 6-2. $SO_2$ and HCl removal efficiency as a function of stoichiometric ratio at Munich.

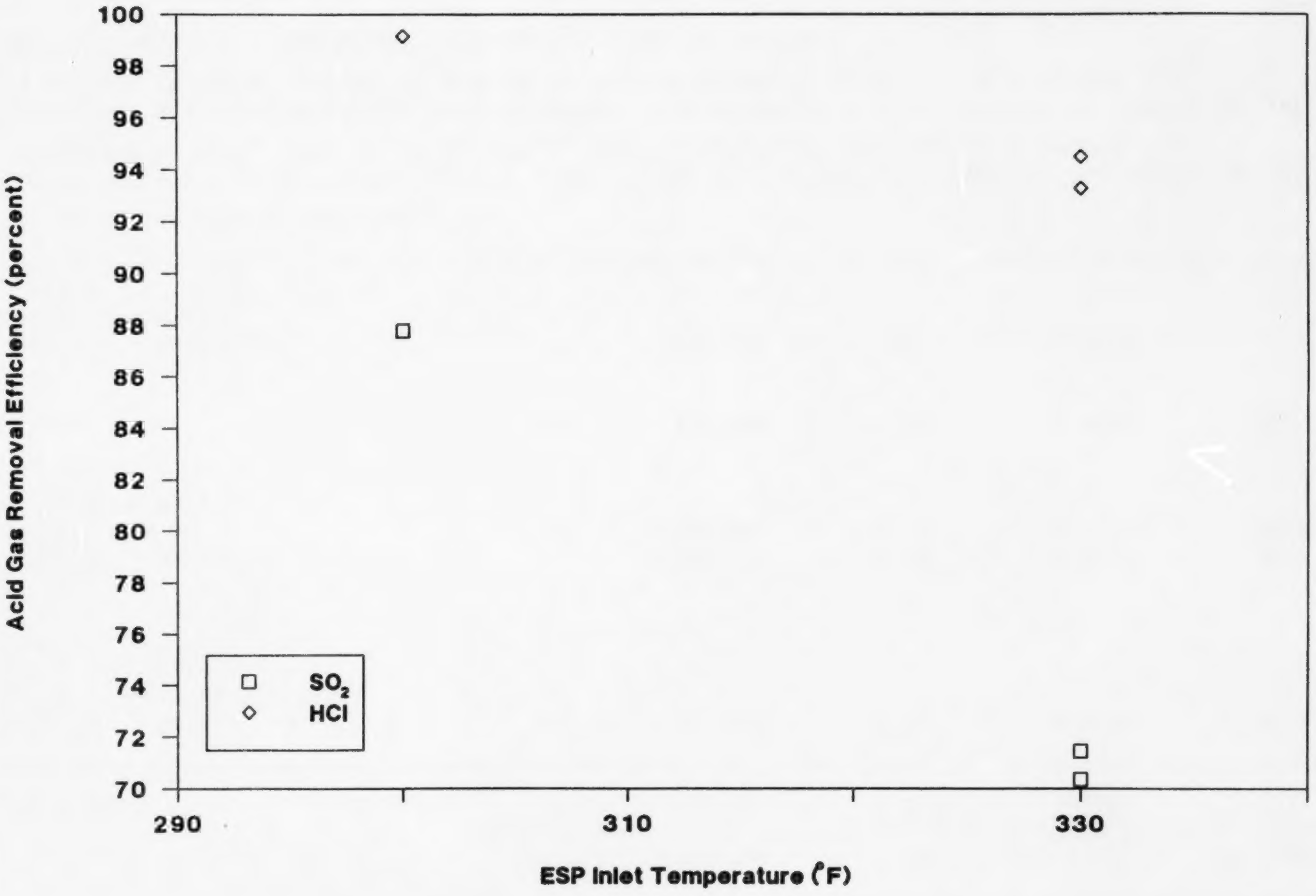

Figure 6-3. $SO_2$ and HCl removal efficiency as a function of ESP inlet temperature at Munich.

## TABLE 6-6. PARTICULATE DATA FOR MUNICH

| Test Condition | Run Number | ESP Inlet Temperature (°F) | Flue Gas Flow (acfm) | PM Concentration (gr/dscf at12% $CO_2$) |  | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
|  |  |  |  | Inlet | Outlet |  |
| Combustor = Normal<br>SD/ESP = Very low SD outlet temperature (266°F)[a] | 2 | 300 | 155,400 | 2.74 | 0.0090 | 99.7 |
| Combustor = Normal<br>SD/ESP = Low SD outlet temperature (293°F)[b] | 3<br>4 | 330<br>330 | 146,400<br>154,800 | 2.22<br>3.72 | 0.0065<br>0.0082 | 99.7<br>99.8 |
| Average |  | 330 | 150,600 | 2.97 | 0.0074 | 99.8 |
| Combustor = Normal<br>SD/ESP = Normal (320°F)[c] | 5 | 314 | 144,900 | NM[d] | 0.0175 | -- |

[a] Constant lime slurry feed rate.

[b] Outlet HCl analyzer/controller used to control lime slurry feed rate. Outlet HCl controller set to achieve 30 mg/Nm$^3$ wet, at 11 percent $O_2$ (approximately 32 ppmv, dry at 7 percent $O_2$).

[c] Outlet HCl analyzer/controller used to control lime slurry feed rate. Outlet HCl controller set to achieve 15 mg/Nm$^3$, wet at 11 percent $O_2$ (approximately 16 ppmv, dry at 7 percent $O_2$).

[d] NM = Not measured. Sample not collected at inlet for Run 5.

TABLE 6-7. METALS EMISSIONS DATA FOR MUNICH

| Test Condition | Run | ESP Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration[a] (ug/dscm at 7% $O_2$) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Ni |
| Combustor = Normal[b]<br>SD/ESP = Normal | 1 | 300 | 0.031 | 1.34 | 25 | 3,020 | 260 | 1,400 |

[a] Results based on approximately 40 continuous hours of sampling with a particle sizing train. Particle fractions and impingers were analyzed for metals.

[b] The system was not kept at a single operating condition during testing and emissions should be considered as "worst-case" only.

The outlet chromium and nickel levels are unusually high. As a result, removal efficiencies for both chromium and nickel, based on typical uncontrolled levels, were near zero. The ratio of chromium concentration to nickel concentration is 2.16, similar to the ratio of chromium to nickel in 18/8 stainless steel (2.25), suggesting that sample contamination may have occurred from the stainless steel in the sampling train.[7]

### 6.2.3 Portland[8]

The Greater Portland Resource Recovery Facility in Portland, Maine, consists of two L. & C. Steinmuller mass burn waterwall combustors, each designed to combust 250 tons/day of MSW. The flue gas exiting the combustor and heat recovery system flows through a SD/ESP system manufactured by Belco Pollution Control Corporation. The flue gas first flows through a cyclone preseparator that removes approximately 50 percent of the fly ash. The flue gas then flows upward through the SD absorption section. In the absorption section, lime slurry is injected through two-fluid nozzles to remove acid gases. The lime slurry feed rate is continuously controlled based on the outlet $SO_2$ level and the dilution water rate is continuously controlled based on the SD outlet temperature. The flue gas flow rate exiting the SD is typically 56,000 acfm at $290^{\circ}F$. The flue gas then passes through a 5-field rigid ESP. The SCA of the ESP is unavailable.

In September 1988, compliance testing was conducted at both the North and South units. Both combustors were at normal operating conditions, but the South unit ESP had one field continuously shorted out and other fields intermittently shorted out during testing. The North ESP operated normally throughout testing. At the SD/ESP inlet and outlet, $SO_2$ and HCl were sampled. At the SD/ESP outlet only, PM, metals (lead, cadmium, chromium), CDD/CDF, and $NO_x$ were measured. Because of the shorted ESP field on the South unit, damaged PM and metals samples, and improperly calibrated equipment for the HCl samples, only the $SO_2$ data from both units and the CDD/CDF data from the North unit are reported here.

Acid gas data for Portland are presented in Table 6-8. Outlet $SO_2$ concentrations for three runs at each of the North and South units ranged from 15 to 35 ppm with the exception of Run 1 at the South unit at 112 ppm.

TABLE 6-8. ACID GAS DATA FROM PORTLAND

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F) | Lime Feed Rate (lb/hr) | $SO_2$ Concentration (ppmv, dry at 7% $O_2$) Inlet | Outlet | $SO_2$ Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Combustor = Normal | N-1 | 285 | 241 | 441 | 31.5 | 92.9 |
| SD/ESP = Normal | N-2 | 285 | 269 | 331 | 34.5 | 89.6 |
| | N-3 | 288 | 304 | 195 | 29.2 | 85.3 |
| Average (North Unit) | | 286 | 271 | 322 | 31.7 | 89.3 |
| | S-1 | 315 | 292 | 437 | 112 | 74.4 |
| | S-2 | 300 | 280 | 194 | 20.1 | 89.6 |
| | S-3 | 286 | 293 | 211 | 14.6 | 93.1 |
| Average (South Unit) | | 300 | 288 | 281 | 48.9 | 85.7 |

[a] Run Number consists of unit identification (N = north, S = south) followed by the run number.

The average outlet $SO_2$ concentration was 32 ppm at the North unit and 49 ppm at the South unit. Removal efficiencies for $SO_2$ were similar for both units, ranging from 74 to 93 percent and averaging 89 percent at the North unit and 86 percent at the South unit.

The effect of ESP inlet temperature on $SO_2$ removal efficiency is shown in Figure 6-4. Removal efficiencies were lowest at $315^oF$. During the tests at 300 and $285^oF$, $SO_2$ removal efficiencies were similar. There was no apparent effect of lime feed rate on $SO_2$ removal of emissions, although the lime feed rate varied from 240 to 300 lb/hr.

Table 6-9 presents CDD/CDF data for Portland. Outlet CDD/CDF concentrations at the North unit ranged from 61.9 to 263 ng/dscm at 7 percent $O_2$ over three runs and averaged 173 ng/dscm. There was no observed effect of ESP inlet temperature on CDD/CDF outlet concentration because there was only a $3^oF$ variation at the ESP inlet.

## 6.3 SUMMARY OF PERFORMANCE

Section 6.2 discussed SD/ESP performance for individual SD/ESP systems. This section combines the data from these facilities to examine the relationship between key design and operating variables and SD/ESP performance.

### 6.3.1 Acid Gas

Acid gas performance for SD/ESP systems was relatively consistent for the three existing facilities. Millbury, Munich, and Portland each achieved greater than 70 percent $SO_2$ removal efficiency during all test conditions. The corresponding $SO_2$ emissions were less than 112 ppm at 7 percent $O_2$. During testing at Munich and Portland when ESP inlet temperatures were $300^oF$ or less, $SO_2$ removal efficiencies exceeded 85 percent and $SO_2$ emissions were 32 ppm or less. The stoichiometric ratio at Munich was 2.1. At Millbury, $SO_2$ removal efficiencies averaged 76 percent, and outlet $SO_2$ emissions averaged 58 ppm at 7 percent $O_2$, even though the ESP outlet temperature was below $255^oF$. The stoichiometric ratio was estimated to be 1.3. HCl removal efficiency at Munich and Millbury was above 96 percent for the tests at $300^oF$ or less. The maximum outlet HCl concentration at these conditions was 31 ppm at 7 percent $O_2$, with averages less than 23 ppm.

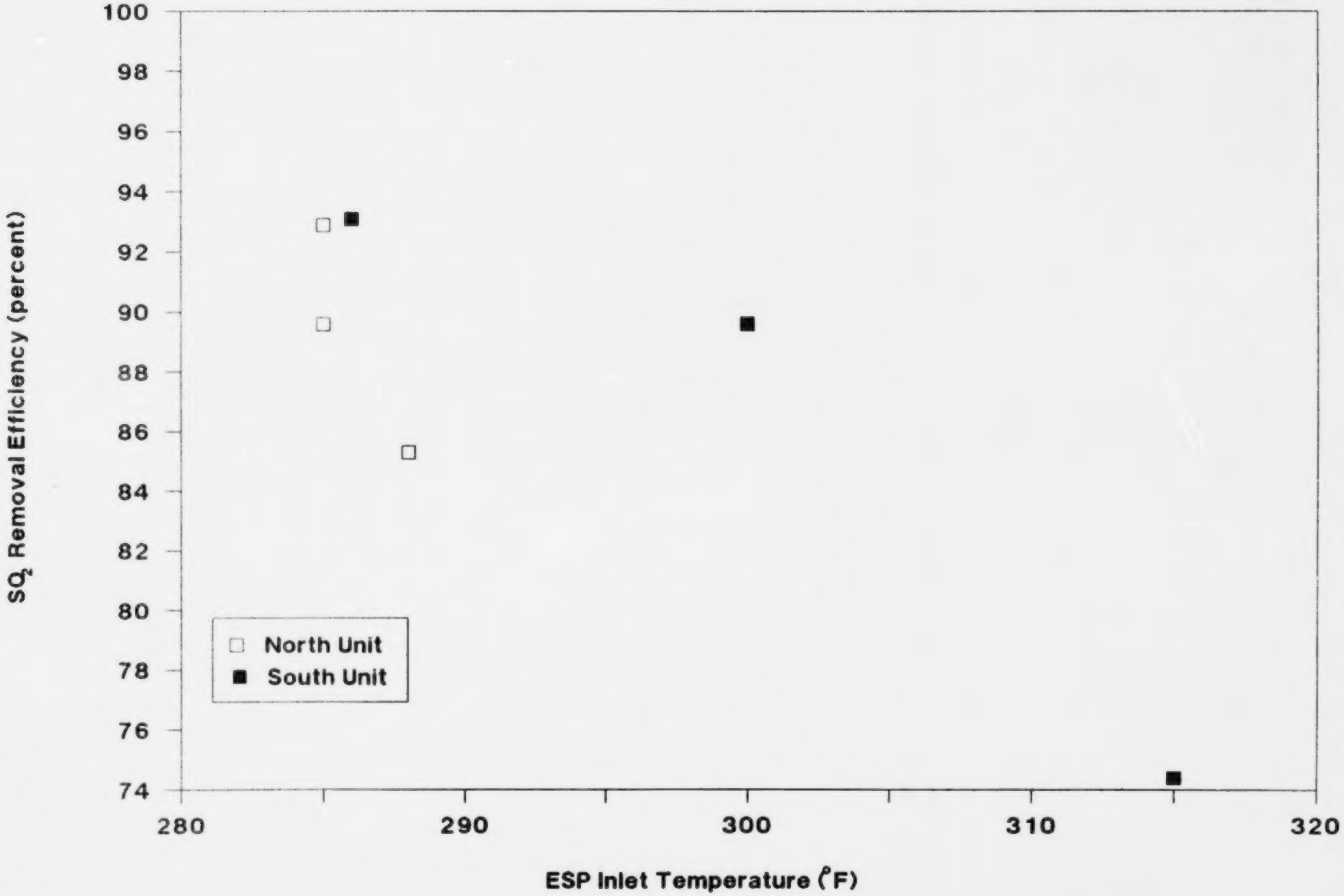

Figure 6-4. SO$_2$ removal efficiency as a function of ESP inlet temperature at Portland.

## TABLE 6-9. CDD/CDF DATA FOR PORTLAND

| Test Condition | Run Number[a] | ESP Inlet Temperature (°F) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | N-1 | 285 | 263 |
| | N-2 | 285 | 62 |
| SD/ESP = Normal | N-3 | 288 | 195 |
| Average | | 286 | 173 |

[a] Run Number consists of unit identifcation (N = north, S = south) followed by the run number.

Analysis of these data suggests that the most important of the variables affecting acid gas removal efficiency is SD outlet temperature. At Munich and Portland, $SO_2$ removal efficiencies generally increased during tests conducted at lower temperatures. Similar phenomena were observed for HCl at Munich. An approximate stoichiometric ratio of 1.3 at Millbury yielded performance similar to Munich at a ratio of 1.2, but the temperature at Munich was $80^{0}F$ higher. This suggests that there is no effect of temperatures below $300^{0}F$ on acid gas removal.

Stoichiometric ratio apparently has a secondary effect on acid gas control with a SD/ESP. At Munich, $SO_2$ and HCl removal efficiencies increased when both ESP outlet temperature decreased and stoichiometric ratio increased. Whether the temperature or the stoichiometric ratio had a greater effect could not be ascertained. At Millbury, the stoichiometric ratio was lower than at the $300^{0}F$ tests at Munich (1.3 versus 2.1), and both $SO_2$ and HCl removal efficiencies were lower, indicating that the lower ratio at Millbury may have led to the decreased performance. However, changes in lime feed rate at Portland of 60 lb/hr (the stoichiometric ratio could not be calculated because no HCl data were available), caused no change in $SO_2$ removal efficiency or outlet concentration. These data suggest that increasing the stoichiometric ratio up to roughly 2 can increase acid gas removal across a SD/ESP system. However, further increases in stoichiometric ratio do not appear to enhance acid gas removal.

Data from SD/FF systems (Section 7.3.1) show that significant acid gas removal occurs after the spray dryer in the fabric filter. In this case, increasing the stoichiometric ratio increases the amount of unreacted sorbent in the fabric filter for secondary removal. An ESP does not provide similar opportunities for secondary reaction of acid gases due to gas-solid contact between the flue gas and collected particulate. As a result, virtually all the acid gas removal in a SD/ESP system must occur in the spray dryer, and the amount of removal across the spray dryer is apparently limited.

Based on these data, average removal efficiencies of 75 percent for $SO_2$ and 95 percent for HCl are achievable during short-term compliance-type tests from SD/ESP systems operating at less than 300°F and stoichiometric ratios of about 2. Outlet $SO_2$ and HCl emissions of 60 ppm and 30 ppm, respectively, are achievable at these conditions. Long-term acid gas control levels are discussed in Appendix A.

### 6.3.2 Particulate Matter

Particulate removal was similar for Millbury and Munich. Each unit averaged 0.010 gr/dscf at 12 percent $CO_2$ or less. Increasing the lime feed rate at Munich did not cause outlet PM concentrations to increase. Thus, average PM emissions of 0.01 gr/dscf at 12 percent $CO_2$ or less are achievable by this technology.

### 6.3.3 Metals

Although uncontrolled metals concentrations were not measured at any of the SD/ESP facilities, estimated removal efficiencies for arsenic, cadmium, lead and nickel were 98 to 99 percent. Chromium removal was estimated at 95 percent at Millbury. Although unusually high chromium and nickel emissions were measured at Munich, these data do not appear to be representative and may have resulted from contamination by the stainless steel sampling probe. Measured outlet mercury emissions at Millbury were relatively high and are comparable to inlet mercury levels measured at other MWC's, indicating that little or no mercury removal occurred.

Metals removal efficiencies by SD/ESP systems of 98 percent are achievable for arsenic, cadmium, lead, and nickel. Chromium removal of 95 percent is achievable. Mercury is not effectively removed by a SD/ESP system.

### 6.3.4 CDD/CDF

CDD/CDF emissions were measured at Millbury and Portland. Outlet concentrations were relatively consistent at Millbury, but varied by up to a factor of 4 at Portland. The outlet CDD/CDF concentrations at Millbury were between 40 and 58 ng/dscm at 7 percent $O_2$ for five of the six runs and 103 ng/dscm at 7 percent $O_2$ during the sixth run. Removal efficiencies for

CDD/CDF at Millbury were measured between 51 and 71 percent and did sl.ow any dependence on inlet CDD/CDF concentrations. The average ESP inlet temperature at Millbury was between 250 and 255$^{0}$F during each test. Outlet CDD/CDF concentrations at Portland were 62, 195, and 263 ng/dscm at 7 percent $O_2$. The ESP inlet temperature was about 35$^{0}$F higher at Portland than at Millbury, suggesting that increased temperature may have affected the results at Portland. CDD/CDF removal efficiencies across the SD/ESP at Portland could not be calculated due to lack of inlet samples.

Because of the limited amount of available data, determination of a consistently achievable performance level is not possible. Based on the Millbury data, CDD/CDF removal efficiency across a SD/ESP operating at the gas temperatures of 250 to 255$^{0}$F is estimated at 50 to 75 percent. The data also suggest that outlet CDD/CDF emissions may increase at higher ESP inlet temperatures.

## 6.4 REFERENCES

1. Masters, K. Spray Drying Handbook, Third Edition. George Godwin Limited. London. 1979. pp. 24 - 27, 150.

2. Brown, B., et al,. (Joy Technologies, Inc.), Dust Collector Design Considerations for MSW Acid Gas Cleaning Systems. Presented at: 7th EPA/EPRI Particulate Symposium. Nashville, Tennessee. March 1988, p. 4.

3. Entropy Environmentalists, Inc. Municipal Waste Combustion Multi-Pollutant Study, Summary Report, Wheelabrator Millbury, Inc., Millbury, Massachusetts. Prepared for U.S. Environmental Protection Agency. Research Triangle Park, North Carolina. EMB Report No. 88-MINO-07A. February 1989.

4. Entropy Environmentalists, Inc. Emissions Testing Report, Wheelabrator Millbury, Inc. Resource Recovery Facility, Millbury, Massachusetts, Unit Nos. 1 and 2, February 8 through 12, 1988. Prepared for Rust International Corporation. Reference No. 5605-B. August 5, 1988.

5. Entropy Environmentalists, Inc. Stationary Source Sampling Report, Wheelabrator Millbury, Inc., Resource Recovery Facility, Millbury, Massachusetts, Mercury Emissions Compliance Testing, Unit No. 1, May 10 and 11, 1988. Prepared for Rust International Corporation. Reference No. 5892-A. May 18, 1988.

6. Hahn, J. L., et al., (Cooper Engineers) and J. A. Finney, Jr. and B. Bahor (Belco Pollution Control Corp.). Air Emissions Tests of a Deutsche Babcock Anlagen Dry Scrubber System at the Munich North Refuse-Fired Power Plant. Presented at: 78th Annual Meeting of the Air Pollution Control Association. Detroit, Michigan. June 1985.

7. Telecon. M.A. Vancil, Radian with J. L. Hahn, Ogden Projects, inc., July 1989. Metals results from tests at the Munich MWC.

8. Engineering Science, Inc. A Report on Air Emission Compliance Testing at the Regional Waste Systems, Inc. Greater Portland Resource Recovery Project. Prepared for Dravo Energy Resources, Inc. Pittsburg, Pennsylvania. March 1989.

# 7.0 SPRAY DRYING FOLLOWED BY A FABRIC FILTER

Section 7.0 describes the technology and performance of spray dryer systems with a FF for PM control. In Section 7.1, SD/FF operation and design is described. Section 7.2 presents descriptions of facilities with emissions data, and summarizes the available data from each facility. In Section 7.3, the performance of SD/FF systems relative to the control of acid gases, PM, metals, and CDD/CDF emissions is discussed.

## 7.1 PROCESS DESCRIPTION

Spray dryers were originally applied to MWC's to control acid gas emissions. A description of the spray drying process and factors affecting performance are discussed in Section 6.1. Fabric filter design and operation is discussed in Section 4.1. There is little difference between FF operation as discussed in Section 4 for duct sorbent injection systems and FF operations following a SD. The particulate following a SD may contain more moisture than a FF following a dry injection system, but this depends on the types of cooling used. Using humidification to cool flue gas in dry sorbent injection systems will generate a particulate with similar moisture content to that following a spray dryer. Alternatively, if heat recovery or mixing with ambient air is used to cool flue gas in a dry injection system, the particulate will have less moisture than that following a spray dryer.

## 7.2 SUMMARY OF TEST DATA

Section 7.2 presents the available emissions data for MWC facilities with SD/FF systems. A description of each facility and a summary and analysis of the emissions data are provided for each facility.

The effects of stoichiometric ratio, FF inlet temperature, and uncontrolled acid gas concentrations on acid gas removal are discussed in each section. The effect of air-to-cloth ratio on PM removal is also discussed. Finally, the effects of inlet CDD/CDF concentration and FF inlet temperature on CDD/CDF removal are discussed.

### 7.2.1 Biddeford[1,2]

Maine Energy Recovery Company's (MERC) York County Waste-to-Energy Facility in Biddeford, Maine, is designed to combust 300 tons per day of RDF in each of two identical Babcock and Wilcox "controlled combustion zone" boilers with traveling grates. The RDF has a nominal top size of 4 inches. Approximately 105,000 lbs per hour of steam are generated by each unit. In each combustor, heat for steam generation is recovered in the furnace waterwalls, superheater, economizer, and combustion air heater sections. At the air heater exit, the flue gas temperature is approximately 400°F.

Emissions from each boiler are controlled by a cyclone, spray dryer, and fabric filter system. The combustion gases from the air heater enter a cyclone-type mechanical dust collector which removes large particulate. Next, an alkaline spray dryer is used to control acid gas emissions. The system is controlled to remove $SO_2$ to an outlet setpoint concentration of 30 ppm. The spray dryer outlet temperature is typically 280 to 300°F.

The lime-to-$SO_2$ stoichiometric ratio and the flue gas temperature at the exit of the spray dryer can be controlled separately. The lime, which is introduced as slurry through a rotary atomizer, is diluted with water before entering the reaction vessel to achieve the desired $SO_2$ outlet concentration and temperature reduction. The $SO_2$ concentration at the stack is monitored and used to control the slurry feed rate.

Particulate in the gas stream is collected by the fabric filter. The fabric filter is a pulse-jet design with fiberglass bags. The design net air-to-cloth ratio is approximately 5.2 acfm/$ft^2$ at a flue gas flow rate of 72,000 acfm at 280°F and 15 percent moisture. The pressure drop across the fabric filter is about 8 inches water column. The fabric filter has six compartments, with 126 bags in each compartment. Five compartments filter flue gas while one compartment is being cleaned in a continuous cycle. The total time to complete a fabric filter cleaning cycle is about 18 minutes. Flue gas from each fabric filter is exhausted through a 244-foot stack that is common to both trains.

In December 1987, emissions testing was performed by EPA to compile emissions data from an RDF combustor with a SD/FF emission control system to support regulations development for MWC's under Section 111 of the

Clean Air Act. The combustor and SD/FF were at normal operating conditions during testing. Three runs were performed at the SD/FF inlet of Unit A and the common SD/FF outlet location. Flue gas samples were collected and analyzed for CDD/CDF, PM, $SO_2$, HCl, $NO_x$, cadmium, chromium, arsenic, lead, and mercury. Additionally, HCl was measured at the spray dryer outlet (SD/FF midpoint) during testing. Process data, including the lime slurry feed rate and lime concentration, were monitored during testing.

Acid gas data from three test runs are presented in Table 7-1. At a consistent average SD outlet temperature of $278^{o}F$, outlet $SO_2$ concentrations ranged from 13.6 to 30.5 ppm at 7 percent $O_2$ and averaged 23 ppm. The corresponding $SO_2$ removal efficiency ranged from 66 to 89 percent and averaged 76 percent. Relatively low inlet $SO_2$ concentrations of 86 to 129 ppm were measured. Outlet HCl concentrations ranged from 3.4 to 9.7 ppm at 7 percent $O_2$ and averaged 5.8 ppm. The corresponding removal efficiencies were between 98.1 and 99.4 percent, averaging 98.9 percent.

Figures 7-1 and 7-2 present graphs of $SO_2$ and HCl removal efficiency, respectively, as functions of stoichiometric ratio. As the stoichiometric ratio increased from 1.7 (Run 1) to 3.9 (Run 3), $SO_2$ removal efficiency increased from 65 to 90 percent and HCl removal efficiency increased from 98 to 99.4 percent. Thus, especially for $SO_2$, but also for HCl, increasing the stoichiometric ratio increased acid gas removal efficiency. Inlet acid gas concentrations did not affect acid gas removal at Biddeford.

In Table 7-2, PM data are presented. Outlet PM concentrations ranged from 0.0095 to 0.019 gr/dscf at 12 percent $CO_2$ and averaged 0.014 gr/dscf. The PM removal efficiency averaged 99.5 percent. The SD/FF system at Biddeford operated with a net air-to-cloth ratio of about 5.7 acfm/$ft^2$.

In Table 7-3, metals data are presented. Except for lead, none of the metals sampled were detected at the SD/FF outlet. The outlet lead concentrations averaged 159 ng/dscm at 7 percent $O_2$. Removal efficiencies for all the metals were at least 99.4 percent, roughly equal to the PM removal efficiency.

## TABLE 7-1. ACID GAS DATA FOR BIDDEFORD

| Test Condition | Run Number | FF Inlet Temperature (°F) | Stoichiometric Ratio | Acid Gas Concentration (ppmv, dry at 7% $O_2$) | | | | | Intermediate HCl Removal Efficiency (percent) | | Overall Acid Gas Removal Efficiency (percent) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Inlet | | Midpoint | Outlet | | | | | |
| | | | | $SO_2$ | HCl | HCl | $SO_2$ | HCl | SD | FF | $SO_2$ | HCl |
| Combustor = Normal | 1 | 277 | 1.7 | 88.7 | 509 | 65 | 30.5 | 9.68 | 26.7 | 85.1 | 65.6 | 98.1 |
| SD/FF = Normal | 2 | 278 | 2.8 | 86.1 | 634 | 8.5 | 23.6 | 4.46 | 90.1 | 47.5 | 72.6 | 99.3 |
| | 3 | 279 | 3.9 | 129 | 603 | 1.1[a] | 13.6 | 3.40 | 99.2 | -210[b] | 89.4 | 99.4 |
| Average | | 278 | 2.8 | 101 | 582 | 24.9 | 22.6 | 5.84 | 72.0 | 44.2 | 75.9 | 98.9 |

[a] Value considered questionable.

[b] Negative HCl removal efficiency suggests that little or no HCl removal occurred across the FF. Midpoint and outlet values within 2 ppm. Considered as zero in evaluating average removal efficiency.

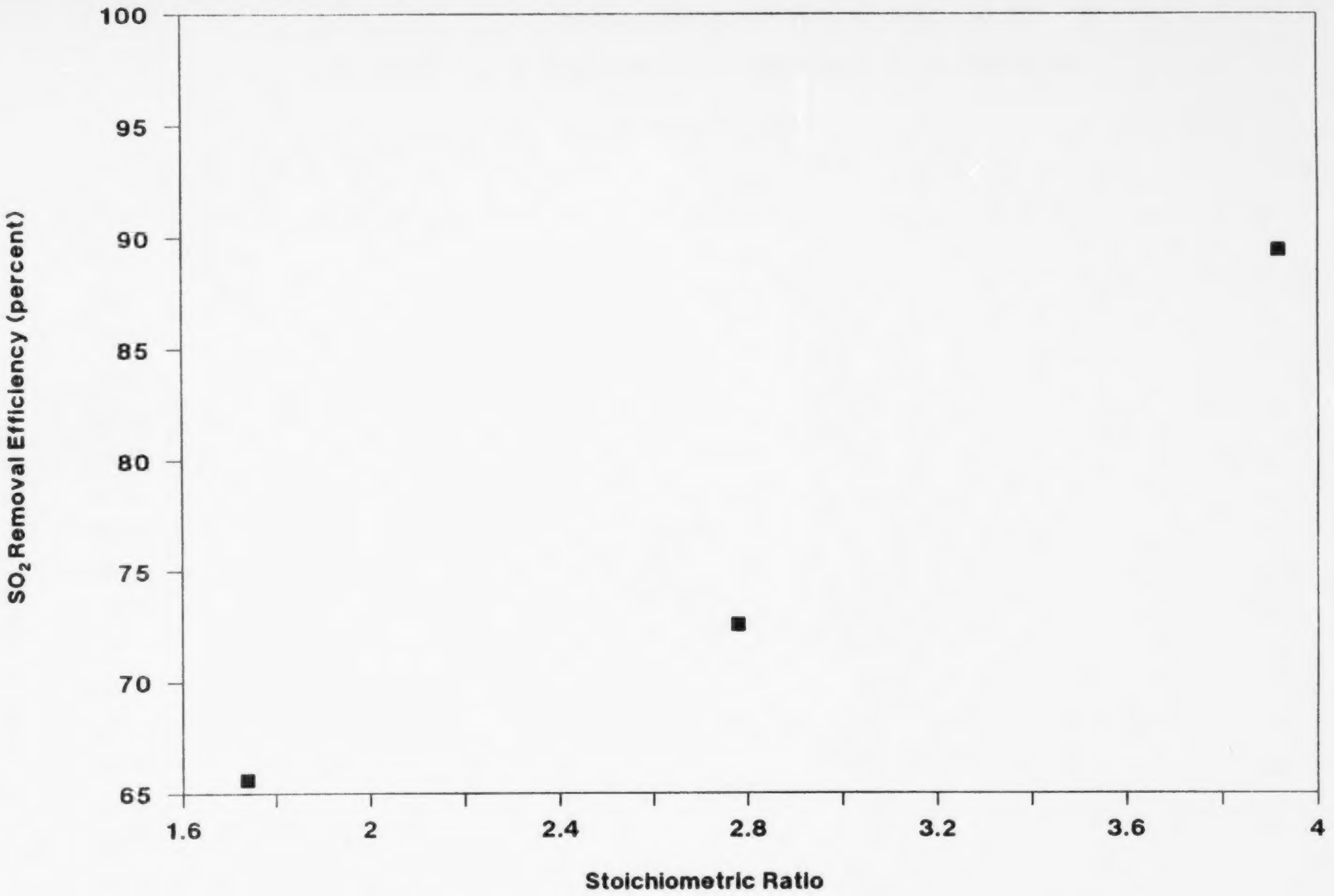

Figure 7-1. $SO_2$ removal efficiency as a function of stoichiometric ratio at Biddeford.

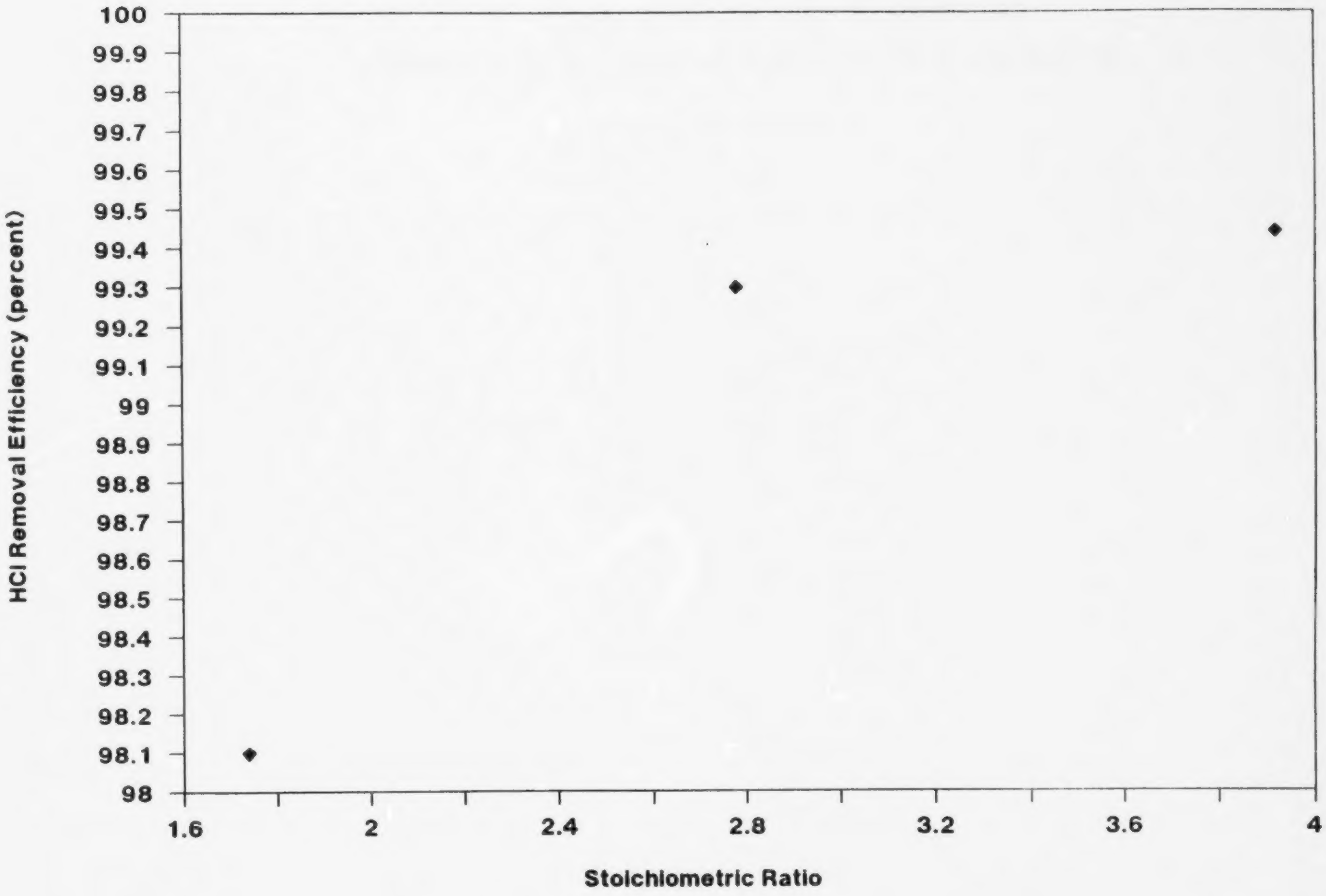

Figure 7-2. HCl removal efficiency as a function of stoichiometric ratio at Biddeford.

TABLE 7-2. PARTICULATE DATA FOR BIDDEFORD

| Test Condition | Run Number | FF Inlet Temperature ($^{o}$F) | Flue Gas Flow (acfm) | PM Concentration (gr/dscf at 12% $CO_2$) |  | PM Removal Efficiency (%) |
|---|---|---|---|---|---|---|
|  |  |  |  | Inlet | Outlet |  |
| Combustor = Normal<br>SD/FF = Normal | 1 | 277 | 77,200 | 3.23 | 0.0095 | 99.7 |
|  | 2 | 278 | 77,800 | 2.85 | 0.014 | 99.5 |
|  | 3 | 279 | 83,000 | 3.53 | 0.019 | 99.4 |
| Average |  | 278 | 79,300 | 3.20 | 0.014 | 99.5 |

TABLE 7-3. METALS DATA FOR BIDDEFORD

| Test Condition | Run Number | FF Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Inlet Concentration ($\mu$g/dscm at 7% $O_2$) | | | | | Outlet Concentration ($\mu$g/dscm at 7% $O_2$) | | | | | Removal Efficiency (Percent)[a] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | As | Cd | Cr | Pb | Hg | As | Cd | Cr | Pb | Hg |
| Combustor = Normal<br>SD/ESP = Normal | 1 | 277 | 0.0095 | 474 | 1,016 | 2,360 | 26,380 | 493 | ND[b] | ND | ND | 146 | ND | 100 | 100 | 100 | 99.5 | 100 |
| | 2 | 278 | 0.014 | 527 | 1,058 | 2,671 | 27,436 | 324 | ND | ND | ND | 155 | ND | 100 | 100 | 100 | 99.4 | 100 |
| | 3 | 279 | 0.019 | 527 | 1,268 | 3,205 | 28,240 | 351 | ND | ND | ND | 177 | ND | 100 | 100 | 100 | 99.4 | 100 |
| Average | | 278 | 0.014 | 509 | 1,114 | 2,745 | 27,352 | 389 | ND | ND | ND | 159 | ND | 100 | 100 | 100 | 99.4 | 100 |

[a] Removal efficiencies reported as 100 percent when compound not detected at outlet.

[b] ND = not detected. Considered as zero in calculating and removal efficiency.

Table 7-4 presents the CDD/CDF data. Outlet CDD/CDF concentrations ranged from 3.5 to 5.2 ng/dscm at 7 percent $O_2$ and averaged 4.4 ng/dscm. Inlet CDD/CDF concentrations were relatively consistent, ranging from 856 to 987 ng/dscm at 7 percent $O_2$, with an average of 903 ng/dscm. The corresponding removal efficiencies averaged 99.5 percent. Thus, the SD/FF at Biddeford operating at $278^0$F, can reduce inlet CDD/CDF concentrations of nearly 1000 ng/dscm to 5.0 ng/dscm CDD/CDF or less at the outlet, with a removal efficiency exceeding 99 percent.

### 7.2.2 Commerce[3,4]

The Commerce Refuse to Energy Facility, in Commerce, California, consists of one mass burn waterwall Foster-Wheeler combustor with a Detroit Stoker grate. The design capacity is 380 tons/day of solid waste, generally commercial waste. Emissions are controlled by Exxon's Thermal $DeNO_x$ system, and a Teller/American Air Filter (AAF) spray dryer and fabric filter. The Thermal $DeNO_x$ system injects ammonia into the upper combustion chamber to reduce $NO_x$ emissions to elemental nitrogen and water. Following heat recovery, the flue gases then enter a cyclonic separator to remove large particles before entering the up-flow SD. In the SD, lime slurry is injected through two-fluid nozzles at a design feed rate of 600 lb/hr of lime. A residence time of 10 seconds is provided in the SD vessel. The design flue gas temperature at the SD outlet is $270^0$F. Tesisorb® is injected into the flue gas through a venturi after leaving the SD to enhance collection performance and to assist conditioning of the filter cake. The FF uses reverse air cleaning with eight compartments each containing 156 fiberglass bags. The design net air-to-cloth ratio is 2 acfm/$ft^2$ with two compartments off-line and a flue gas flow of about 85,000 acfm. The flue gas leaves the FF and exits through a 150-foot high stack.

Several major test programs have been conducted at the Commerce MWC facility. In May and June 1987, compliance testing was performed at the facility. The combustor and $DeNO_x$/SD/FF system were generally operated at normal conditions. The combustor routinely fired mainly commercial refuse. One run (17) fired residential refuse. Flue gas at the SD/FF inlet and outlet were analyzed for $SO_2$, HCl, HF, PM, CDD/CDF, and metals (antimony,

TABLE 7-4. CDD/CDF DATA FOR BIDDEFORD

| Test Condition | Run Number | FF Inlet Temperature (°F) | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (percent) |
|---|---|---|---|---|---|
| Combustor = Normal | 1 | 277 | 856 | 4.45 | 99.5 |
| SD/FF = Normal | 2 | 278 | 866 | 5.18 | 99.4 |
|  | 3 | 279 | 987 | 3.51 | 99.6 |
| Average |  | 278 | 903 | 4.38 | 99.5 |

arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, thallium, and zinc). Inlet PM and $SO_2$ samples were not collected simultaneously with the outlet samples. $NO_x$ was measured at the FF outlet. The lime feed rate during this test was not measured, but was estimated to be at 600 lb/hr, the design rate.

In June 1988, a series of tests were conducted to optimize $NO_x$ removal efficiency by the Thermal $DeNO_x$ system at Commerce. These results, along with results of other tests of $NO_x$ removal systems, are presented in a separate EPA document entitled "Municipal Waste Combustors--Background Information for Proposed Standards: Control of $NO_x$ Emissions."[6]

In July 1988, additional testing was conducted at the Commerce facility as part of the California Waste Management Board's Waste-to-Energy Demonstration Program. Emissions were measured while firing commercial refuse and a mixture of residential and commercial refuse. Three runs were conducted with each feed type. The objectives of the program were to fully characterize the incoming waste stream, the air pollution control equipment performance and emissions, and the ash residue. The $DeNO_x$/SD/FF system was operated normally during testing. At the SD inlet and FF outlet, samples were collected and analyzed for $SO_2$, HCl, PM, metals (arsenic, cadmium, chromium, lead, mercury, nickel, and others), CDD/CDF, other organics, HF, and $NO_x$. Data from both test programs are presented below.

Acid gas data are presented in Table 7-5. Outlet $SO_2$ concentrations ranged from 0.78 to 8.0 ppm at 7 percent $O_2$ over nine test runs. Removal efficiencies, recorded during the 1988 testing, were between 93.4 and 99.5 percent and averaged 97.9 percent. Outlet HCl concentrations ranged from 3.2 to 11.1 ppm at 7 percent $O_2$ over eight runs. The average removal efficiency during two test runs in 1987 was 99.1 percent and was 98.9 percent during the 1988 testing. Stoichiometric ratio data are estimated based on an assumed lime feed rate (600 lb/hr) and the measured inlet $SO_2$ and HCl concentrations for the 1988 tests. No consistent effect of stoichiometric ratio on performance was observed. Fabric filter inlet temperatures during the test were relatively constant at 273 to $297^{o}$F. There was no observed difference in SD performance while burning either residential or commercial refuse.

## TABLE 7-5. ACID GAS DATA FOR COMMERCE

| Test Condition | Run Number | FF Inlet Temperature (°F)[a] | Stoichiometric Ratio | Acid Gas Concentration (ppmv, dry at 7% $O_2$) Inlet $SO_2$[b] | Inlet HCl | Outlet $SO_2$[b] | Outlet HCl | Acid Gas Removal Efficiency (percent) $SO_2$[b] | HCl |
|---|---|---|---|---|---|---|---|---|---|
| Combustor = Normal<br>$DeNO_x$/SD/FF = Normal<br>(1987) | 2 | 283 | NM[c] | NM | NM | 1.3 | NM | -- | -- |
| | 3 | 275 | NM | NM | NM | 1.1 | NM | -- | -- |
| | 4 | 273 | NM | NM | NM | 1.6 | NM | -- | -- |
| | 7 | NA[d] | NM | 359 | NM | NM | NM | -- | -- |
| | 8 | NA | NM | 187 | NM | NM | NM | -- | -- |
| | 15 | NA | NM | NM | 1,079 | NM | 11.1 | -- | 99.0 |
| | 16 | NA | NM | NM | 710 | NM | 6.5 | -- | 99.1 |
| Average | | 277 | NA | 273 | 895 | 1.3 | 8.8 | -- | 99.1 |
| Combustor = Residential/ Commercial Refuse<br>$DeNO_x$/SD/FF = Normal<br>(1988) | 2 | 290 | 3.1[e] | 104 | 764 | 1.1 | 7.0 | 98.9 | 99.1 |
| | 7 | 288 | 5.0[e] | 99 | 415 | 0.9 | 7.0 | 99.1 | 98.3 |
| | 11 | 297 | 2.9[e] | 130 | 758 | 3.8 | 8.0 | 97.1 | 98.9 |
| Average | | 292 | 3.7[e] | 111 | 646 | 1.9 | 7.3 | 98.4 | 98.8 |
| Combustor = Commercial Refuse<br>$DeNO_x$/SD/FF = Normal<br>(1988) | 14 | 290 | 3.1[e] | 161 | 627 | 0.8 | 8.9 | 99.5 | 98.6 |
| | 21 | 282 | 6.3[e] | 114 | 265 | 2.6 | 3.2 | 97.7 | 98.8 |
| | 27 | 285 | 3.2[e] | 120 | 707 | 8.0 | 4.4 | 93.4 | 99.4 |
| Average | | 286 | 4.2[e] | 132 | 533 | 3.8 | 5.5 | 96.9 | 98.9 |

[a] Temperature estimated from measured value at stack and an assumed temperature drop across the fabric filter (10°F).

[b] Total sulfur oxides. $SO_2$ and $SO_3$ not separately reported.

[c] NM = not measured.

[d] NA = not available.

[e] Stoichiometric ratio calculated assuming the design lime feed rate of 600 lb/hr.

In Table 7-6, particulate data are presented. All outlet PM concentrations were below 0.0043 gr/dscf at 12 percent $CO_2$. The observed removal efficiencies were at least 99.8 percent for all ten runs. During two runs in 1987, the PM concentration was measured at the FF inlet and was about 50 percent higher than at the SD inlet because of the lime injected in the SD. The air-to-cloth ratio ranged from 2.1 to 2.4. There was no apparent affect of fuel type on PM removal.

Metals emissions data are presented in Table 7-7. The metals data presented for the May and June 1987 testing are only estimates because 100 ml of the sampling probe rinse was inadvertently discarded prior to analysis. Because this error was not discovered until after the sample fractions were composited, the estimated concentration represents a maximum value. For volatile metals such as arsenic, lead, and mercury, the actual values may be 12 to 25 percent lower than reported since only small amounts of those metals would be expected to be present in the discarded probe rinse fraction. Outlet metals concentrations were similar for both test programs. Average arsenic, cadmium, chromium, lead, and nickel concentrations were less than 6.0 ug/dscm. Removal efficiencies for these metals averaged above 99 percent for both test programs. Mercury emissions averaged 570 ug/dscm during the 1987 tests, but during the 1988 tests, the average outlet concentrations were 39 and 68 ug/dscm (residential and commercial refuse, respectively). This is similarly reflected in mercury removal efficiency data. In 1987, zero mercury removal was indicated. In 1988, mercury removal efficiency ranged from 53.3 to 94.6 percent and averaged 90 percent (residential refuse) and 70 percent (commercial refuse). It has been suggested that the presence of unburned carbon in the flue gas may enhance mercury removal.[5] High inlet CDD/CDF concentrations during the 1988 tests, but not the 1987 tests, indicating elevated carbon content on the fly ash, appears to support this theory.

CDD/CDF data are presented in Table 7-8. As described above, much higher inlet CDD/CDF concentrations were measured in the 1988 tests (233 to 1,010 ng/dscm) than the 1987 tests (28 ng/dscm). However, outlet CDD/CDF concentrations from the two tests were similar, ranging from 0.7 to 3.5 ng/dscm at 7 percent $O_2$. The average outlet CDD/CDF concentrations

## TABLE 7-6. PARTICULATE DATA FOR COMMERCE

| Test Condition | Run Number | FF Inlet Temperature[a] (°F) | Flue Gas Flow (acfm) | PM Concentration (gr/dscf at 12% $CO_2$) | | | PM Removal Efficiency (percent) | |
|---|---|---|---|---|---|---|---|---|
| | | | | Inlet | Midpoint | Outlet | FF | Total |
| Combustor = Normal | 2 | 283 | 90,970 | NM[b] | 2.84 | 0.0022 | 99.9 | -- |
| $DeNO_x$/SD/FF = Normal (1987) | 3 | 275 | 89,520 | NM | 2.43 | 0.0043 | 99.8 | -- |
| | 4 | 273[c] | 89,020 | NM | NM | 0.0022 | -- | -- |
| | 7 | NR | 94,320 | 2.25 | NM | NM | -- | -- |
| | 8 | NR | 97,380 | 1.30 | NM | NM | -- | -- |
| Combustor = Normal<br>$DeNO_x$/SD/FF = $DeNO_x$ off (1987) | 9 | 291 | 88,880 | NM | NM | 0.0019 | -- | -- |
| Average (1987) | | 281 | 91,680 | 1.78 | 2.64 | 0.0027 | 99.9 | 99.8 |
| Combustor = Residential/ Commercial Refuse | 2 | 290 | 103,800 | 2.87 | NM | 0.0010 | -- | 99.97 |
| | 7 | 288 | 91,500 | 1.67 | NM | 0.0016 | -- | 99.9 |
| $DeNO_x$/SD/FF = Normal (1988) | 11 | 297 | 99,700 | 1.48 | NM | 0.0016 | -- | 99.9 |
| Average | | 292 | 98,300 | 2.01 | NM | 0.0014 | -- | 99.9 |
| Combustor = Commercial Refuse | 14 | 290 | 96,800 | 2.16 | NM | 0.0004 | -- | 99.98 |
| | 21 | 282 | 91,500 | 0.65 | NM | 0.0010 | -- | 99.8 |
| $DeNO_x$/SD/FF = Normal (1988) | 27 | 285 | 100,400 | 0.87 | NM | 0.0008 | -- | 99.9 |
| Average | | 286 | 96,200 | 1.23 | NM | 0.0007 | -- | 99.9 |

[a] Temperature estimated from measured value at the stack and an assumed temperature drop across the fabric filter (10°F).

[b] NM = not measured.

[c] NR = not reported.

## TABLE 7-7. METALS EMISSIONS DATA FOR COMMERCE

| Test Condition | Run Number | FF Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Inlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Removal Efficiency (percent) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal | 11[a] | NR[b] | NM[c] | NM | NM | NM | NM | NM | NM | ND[d] | ND | ND | 5.0 | 200 | ND | -- | -- | -- | -- | -- | -- |
| DeNO$_x$/SD/FF = | 13[a] | NR | NM | 190 | 5,300 | 800 | 52,000 | 670 | 770 | ND | ND | ND | 3.3 | 940 | ND | 100 | 100 | 100 | 99.99 | -40 | 100 |
| Normal (1987) | 14[a] | NR | NM | 250 | 2,100 | 660 | 47,000 | 240 | 580 | NM | NM | NM | NM | NM | NM | -- | -- | -- | -- | -- | -- |
| Average (1987) | | NR | NM | 220 | 2,700 | 730 | 50,000 | 450 | 680 | ND | ND | ND | 4.2 | 570 | ND | 100 | 100 | 100 | 99.99 | -40 | 100 |
| Combustor = | 3 | NR | NM | 84 | 1,415 | 7,200 | 4,110 | 681 | 9,849 | 0.02 | 0.6 | 3.1 | 1.5 | 37 | 1.7 | 99.98 | 99.96 | 99.96 | 99.96 | 94.6 | 99.98 |
| Residential/ | 5 | NR | NM | 56 | 1,912 | 1,272 | 24,960 | 336 | 1,893 | ND | 0.4 | 1.4 | 0.5 | 41 | 0.6 | 100 | 99.98 | 99.9 | 100 | 88.0 | 99.97 |
| Commercial Refuse | 9 | NR | NM | 82 | 1,466 | 1,882 | 22,690 | 341 | 392 | 0.42 | 4.6 | 2.2 | 3.6 | 41 | 15.6 | 99.5 | 99.7 | 99.9 | 99.98 | 88.0 | 96.0 |
| DeNO$_x$/SD/FF = Normal (1988) | | | | | | | | | | | | | | | | | | | | | |
| Average | | | | 74 | 1,598 | 3,451 | 17,250 | 453 | 4,045 | 0.15 | 1.9 | 2.2 | 1.9 | 39 | 6.0 | 99.8 | 99.9 | 99.9 | 99.98 | 90.2 | 98.7 |
| Combustor = | 13 | NR | NM | 2 | 1,284 | 551 | 6,822 | 278 | 1,998 | ND | 0.5 | 0.5 | 4.3 | 51 | ND | 100 | 99.96 | 99.9 | 99.9 | 81.8 | 100 |
| Commercial Refuse | 16 | NR | NM | 97 | 17 | 473 | 22,364 | 159 | 3,589 | 0.16 | 0.3 | 0.3 | 2.7 | 74 | 0.4 | 99.8 | 98.5 | 99.9 | 99.98 | 53.3 | 99.98 |
| DeNO$_x$/SD/FF = Normal | 18 | NR | NM | 86 | 1,239 | 957 | 19,007 | 299 | 503 | 1.29[e] | 16.8[e] | 3.4[e] | 340[e] | 29[e] | 2.4[e] | 98.5[e] | 98.6[e] | 99.6[e] | 98.2[e] | 90.5[e] | 99.5[e] |
| (1988) | 29 | NR | NM | 89 | 1,290 | 243 | 13,917 | 308 | 1,299 | ND | 0.4 | ND | 1.6 | 79 | 0.3 | 100 | 99.97 | 100 | 99.98 | 74.4 | 99.98 |
| Average | | | | 69 | 958 | 556 | 15,528 | 261 | 1,847 | 0.05 | 0.4 | 0.3 | 2.9 | 68 | 0.2 | 99.9 | 99.5 | 99.9 | 99.95 | 69.8 | 99.99 |
| Overall Average (1988) | | NR | 0.0017[f] | 71 | 1,232 | 1,797 | 16,310 | 343 | 2,789 | 0.10 | 1.1 | 1.3 | 2.4 | 54 | 3.1 | 99.9 | 99.7 | 99.9 | 99.97 | 80.0 | 99.3 |

[a] Concentrations reported for Runs 11, 13, and 14 of the 1987 tests are estimated maximum values. A known amount of the probe rinse from each sample was inadvertently discarded. The remainder of the rinse was composited with the other sample fractions and the composite was analyzed. For arsenic, lead, and mercury, (which are more volatile and likely not in the probe rinse) the actual value may be 12 to 20 percent lower than the value reported. For the other, less volatile metals, the actual value is probably close to the reported value.

[b] NR = not reported.

[c] NM = not measured.

[d] ND = not detected. Considered as zero in calculating averages and removal efficiencies.

[e] Baghouse had disconnected bag during test. Results not representative and not included in average.

[f] PM samples not collected simultaneously. Average result given.

## TABLE 7-8. CDD/CDF DATA FOR COMMERCE

| Test Condition | Run Number | FF Inlet Temperature (°F) | CDD/CDF Concentration (ng/dscm at 7% $O_2$) Inlet | CDD/CDF Concentration (ng/dscm at 7% $O_2$) Outlet | CDD/CDF Removal Efficiency (%) |
|---|---|---|---|---|---|
| 1987 TESTS | | | | | |
| Combustor = Commercial Refuse<br>$DeNO_x$/SD/FF = Normal | 15 | 265 | NM[a] | 0.92 | -- |
| | 16 | 270 | NM | 1.09 | -- |
| Combustor = Residential Refuse<br>$DeNO_x$/SD/FF = Normal | 17 | 275 | 28.1 | 3.47 | 87.7 |
| Average (1987 Tests) | | 270 | 28.1 | 1.83 | 87.7 |
| 1988 TESTS | | | | | |
| Combustor = Residential/Commercial Refuse<br>$DeNO_x$/SD/FF = Normal | 1[b] | NR[c] | 233[d] | 25.4[d] | 89.1[d] |
| | 4 | NR | NR[d] | 2.37 | -- |
| | 8 | NR | 659[d] | 0.99 | 99.9 |
| Average | | NR | 446 | 9.59 | 94.5 |
| Combustor = Commercial Refuse<br>$DeNO_x$/SD/FF = Normal | 15 | NR | 806 | 3.52 | 99.6 |
| | 17 | NR | 532 | 3.12 | 99.4 |
| | 22 | NR | 1,010[d] | 1.71 | 99.8 |
| Average | | NR | 783 | 2.78 | 99.6 |
| Overall Average (1988 Tests) | | 270 | 545 | 4.73 | 95.9 |

[a] NM = Not measured.

[b] Run 1 had low load, unstable combustor conditions.

[c] NR = Not reported.

[d] Interferences noted for analysis of these samples. Run 4 inlet considered invalid by analytical laboratory.

ranged from 1.8 ng/dscm in 1987 to 1.7 ng/dscm in 1988 for residential refuse to 2.8 ng/dscm in 1988 for commercial refuse. Removal efficiency was 87.7 percent for one run with very low inlet during the 1987 test. During the 1988 tests, removal efficiency was 97 percent. Removal efficiency increased with increasing inlet CDD/CDF concentration. Above inlet CDD/CDF concentrations of 530 ng/dscm, removal efficiencies were all above 99 percent. However, outlet CDD/CDF concentrations were relatively independent of inlet CDD/CDF concentration. The SD/FF system at Commerce can reduce CDD/CDF levels to less than 5.0 ng/dscm, despite inlet CDD/CDF levels as high as 1000 ng/dscm.

### 7.2.3 Long Beach[7]

The Southeast Resource Recovery Facility in Long Beach, California consists of three identical L. & C. Steinmuller GmbH waterwall combustors, each with a capacity of 460 tons/day MSW. Each combustor uses Thermal DeNO$_x$ and flue gas recirculation for NO$_x$ control. Other pollutants are controlled downstream from the boiler with a spray dryer/fabric filter system, manufactured by Flakt-Peabody Process Systems. In the spray dryer, lime slurry is injected through a rotary atomizer. with the rate of slurry addition controlled by an SO$_2$ monitor/controller at the stack. The amount of dilution water in the slime slurry is controlled to maintain temperature at the outlet of the SD. Flue gas existing the SD flows through a reverse-air FF. Design flue gas flow to each FF is 118,000 acfm at 285$^0$F. Each FF has 10 compartments of teflon-coated fiberglass bags and a net air-to-cloth ratio of 1.8 acfm/ft$^2$. Ducting is provided to route flue gas from one FF to another if one unit goes down. Flue gas is exhausted through a common stack.

In November 1988, testing was conducted on Unit 1 to demonstrate compliance with permit conditions. The combustor and the air pollution control equipment operated normally during testing. At the SD/FF inlet and outlet, samples were collected and analyzed for PM and SO$_2$. Particulate was also measured at the SD outlet. At the SD/FF outlet, HCl, metals (arsenic, cadmium, chromium, lead, mercury, and nickel), CDD/CDF, NO$_x$, and other organics were sampled. The $NO_x$ results are reported in Municipal Waste Combustors - Background Information for Proposed Standards: Control of $NO_x$ Emissions.[6]

Acid gas data are presented in Table 7-9. Of the three test runs performed, outlet $SO_2$ concentrations were 5.61 and 7.95 ppm at 7 percent $O_2$ for Runs 2 and 3. During Run 1, the lime slurry feed stopped, resulting in an unrealistically high outlet $SO_2$ concentration. The $SO_2$ removal efficiencies for test Runs 2 and 3 were 92.2 and 96.5 percent, respectively. Outlet HCl concentrations ranged from 13.4 to 38.2 ppm at 7 percent $O_2$ and averaged 24.2 ppm. Outlet HCl sampling was not conducted simultaneously with $SO_2$ sampling. Inlet HCl levels were not measured. The fabric filter inlet temperatures ranged from 303 to 311°F and averaged 307°F during the $SO_2$ tests and ranged from 290 to 300°F and averaged 295°F during the HCl tests. Because of the limited range in fabric filter inlet temperature, the effect of this key process variable on acid gas control performance of the SD/FF can not be evaluated. The lime feed rate was not measured during testing.

Particulate data for Long Beach are presented in Table 7-10. Outlet PM concentrations ranged from 0.0047 to 0.0076 gr/dscf at 12 percent $CO_2$ over three runs and averaged 0.0060 gr/dscf. The corresponding PM removal efficiency across the SD/FF was between 99.4 and 99.7 percent and averaged 99.6 percent. Concentrations at the FF inlet were very similar for the three runs, averaging 2.75 gr/dscf at 12 percent $CO_2$, representing an increase in particulate concentration of 53 to 102 percent across the SD. The flue gas flow rate and resulting air-to-cloth ratio were essentially constant for each run at approximately 1.7 $acfm/ft^2$.

Metals emissions data for Long Beach are presented in Table 7-11. Arsenic, chromium, lead and nickel concentrations at the FF outlet all averaged less than 5 ug/dscm. The average cadmium concentration was 18 ug/dscm. Mercury at the FF outlet averaged 180 ug/dscm. Compared to typical uncontrolled metals concentrations (see Section 1.2), removal efficiencies for arsenic, cadmium, chromium, lead, and nickel are estimated to be at least 99 percent. The measured outlet mercury emissions suggest a removal efficiency of 65 percent based on typical uncontrolled levels. However, because uncontrolled mercury levels vary widely, it is possible that the estimated mercury removal may be significantly less.

TABLE 7-9. ACID GAS DATA FOR LONG BEACH

| Test Condition | Run Number | FF Inlet Temperature[a] ($^{o}$F) | Stoichiometric Ratio | Acid Gas Concentrations[b,c] (ppmv, dry at 7% $O_2$) Inlet $SO_2$ | Outlet $SO_2$ | Outlet HCl | $SO_2$ Removal Efficiency (percent) |
|---|---|---|---|---|---|---|---|
| Combustor = Normal | 1 | 303 290[a] | NA[d] | 154 | 72.2[e] | 13.4 | 53.1 |
| DeNO$_x$/SD/FF - Normal | 2 | 311 295[a] | NA | 102 | 7.6 | 21.0 | 92.2 |
|  | 3 | 307 300[a] | NA | 158 | 5.6 | 38.2 | 96.5 |
| Average |  | 307 295[a] | NA | 138 | 6.8 | 24.2 | 94.4 |

[a] $SO_2$ and HCl measurements were made during separate runs. First temperature is for $SO_2$ runs. Second temperature is for HCl runs. Temperature estimated from measured value at stack and assumed temperature drop of 10$^{o}$F across the fabric filter.

[b] Total sulfur oxides. $SO_2$ and $SO_3$ not separately reported.

[c] $SO_2$ and HCl not measured simultaneously.

[d] NA = not available. Lime slurry feed rate not measured.

[e] Outlet $SO_2$ concentration from Run 1 is considered anomalous because the lime slurry feed stopped during the test. Sampling was stopped during this time interval. Results are not included in average.

TABLE 7-10. PARTICULATE DATA FOR LONG BEACH

| Test Condition | Run Number | FF Inlet Temperature (°F) | Flue Gas Flow (acfm) | PM Concentration (gr/dscf at 12% $CO_2$) |  |  | PM Removal Efficiency (percent) |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | Inlet | Midpoint | Outlet | SD | FF | Overall |
| Combustor = Normal | 1 | 291 | 112,690 | 1.63 | 2.85 | 0.0047 | -74.9 | 99.8 | 99.7 |
| $DeNO_x$/SD/FF = Normal | 2 | 300 | 113,200 | 1.82 | 2.78 | 0.0057 | -52.8 | 99.8 | 99.7 |
|  | 3 | 302 | 113,820 | 1.29 | 2.61 | 0.0076 | -102 | 99.7 | 99.4 |
| Average |  | 298 | 113,240 | 1.58 | 2.75 | 0.0060 | -76.6 | 99.8 | 99.6 |

TABLE 7-11. METALS DATA FOR LONG BEACH

| Test Condition | Run Number | FF Inlet Temperature ($^{o}F$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal<br>$DeNO_x$/SD/FF = Normal | 1 | 291 | 0.0047 | ND[a] | 10.6 | 4.75 | 13.9 | 146 | 2.92 |
| | 2 | 300 | 0.0057 | ND | 9.5 | 1.06 | ND | 176 | 1.76 |
| | 3 | 302 | 0.0076 | ND | 33.8 | 2.09 | ND | 219 | 3.75 |
| Average | | 298 | 0.0060 | ND[b] | 18.0 | 2.63 | 4.6 | 180 | 2.81 |

[a] ND = not detected. Considered as zero for evaluating averages.

[b] Arsenic was not detected in any of the three runs. The maximum detection limit was 33 ug/dscm at 7 percent $O_2$.

Table 7-12 presents the CDD/CDF data from Long Beach. Outlet CDD/CDF concentrations ranged from 1.2 to 9.8 ng/dscm at 7 percent $O_2$ over three runs and averaged 4.14 ng/dscm. The highest CDD/CDF concentration was measured at the highest FF inlet temperature, 313°F. However, the range in temperature, 298 to 313°F, was too limited to evaluate the effect of this parameter. Based on the above, the SD/FF at Long Beach, operating at less than 310°F is capable of achieving outlet CDD/CDF concentrations of less than 10 ng/dscm.

### 7.2.4 Mid-Connecticut[8]

The Mid-Connecticut Resource Recovery Facility in Hartford, Connecticut consists of three Combustion Engineering spreader stoker-fired boilers each designed to combust a maximum of 675 tons/day RDF or 236 tons/day coal. Each RDF combustor is designed to produce 231,000 lb/hr of steam.

The air pollution control system for each combustor consists of a spray dryer followed by a fabric filter. Slaked pebble lime slurry is introduced to the spray dryer through a single rotary atomizer. The slurry feed rate is controlled to achieve the desired $SO_2$ removal and the dilution water flow rate is controlled to achieve the desired temperature at the SD outlet. Upon exiting the SD, the typical flue gas flow is about 190,000 acfm at 280°F. The reverse-air cleaned fabric filter has 12 compartments of 168 teflon-coated glass-fiber bags each and a design gross air-to-cloth ratio of 1.45 acfm/ft$^2$. The net air-to-cloth ratio is 1.74 acfm/ft$^2$ with two compartments off-line.

In July 1988, compliance testing was conducted at the facility. The EPA funded testing at the SD/FF inlet of one of the units during compliance testing to determine the level of uncontrolled MWC emissions and assess the performance of the SD/FF system. The combustor and SD/FF were at normal operating conditions during testing. At the SD/FF inlet and outlet, flue gas was sampled for PM, metals (including arsenic, cadmium, chromium, lead, mercury, and nickel), and CDD/CDF. No acid gas measurements were taken.

Particulate data are presented in Table 7-13. Outlet PM concentrations ranged from 0.0021 to 0.0059 gr/dscf at 12 percent $CO_2$ over three runs and averaged 0.0040 gr/dscf. The corresponding PM removal efficiencies averaged

## TABLE 7-12. CDD/CDF DATA FOR LONG BEACH

| Test Condition | Run Number | FF Inlet Temperature[a] (°F) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1 | 313 | 9.75 |
| | 2 | 298 | 1.47 |
| $DeNO_x$/SD/FF = Normal | 3 | 305 | 1.20 |
| Average | | 305 | 4.14 |

[a] Temperature estimated from measured value at stack and an assumed temperature drop across the FF (10°F).

TABLE 7-13. PARTICULATE DATA FOR MID-CONNECTICUT

| Test Condition | Run Number | FF Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | PM Removal Efficiency (percent) |
|---|---|---|---|---|---|---|
| Combustor = Normal<br>SD/FF = Normal | 1 | 274 | 159,000 | 2.57 | 0.0021 | 99.9 |
| | 2 | 276 | 156,000 | 2.25 | 0.0041 | 99.8 |
| | 3 | 278 | 159,000 | 4.78[a] | 0.0059 | 99.9 |
| Average | | 276 | 158,000 | 2.41 | 0.0040 | 99.9 |

[a] Includes sootblowing cycle. Value not included in average.

99.9 percent. Air-to-cloth ratio was relatively constant among the tests at 1.5 acfm/ft$^2$.

Metals data for Mid-Connecticut are presented in Table 7-14. Three runs were conducted with simultaneous sampling at the inlet and outlet for arsenic, chromium, lead, and nickel. Cadmium and mercury were additionally measured at the inlet only. Inlet sampling was performed using the draft EMSL method and outlet sampling was conducted using EPA Methods 12 and 108. Three additional runs were conducted with mercury, measured simultaneously at the inlet and outlet using EPA Method 101A. Both arsenic and lead were not detected at the outlet during any runs. Chromium was detected in Run 1 at 115 ug/dscm, but not detected in the other two runs. Mercury concentrations ranged from 3.7 to 130 ug/dscm and averaged 50 ug/dscm. Nickel was detected in two runs at 460 and 470 ug/dscm, but not detected in Run 3. Because arsenic and lead were not detected in any of the three outlet samples, removal efficiencies of nearly 100 percent were estimated. Chromium removal efficiency was 88 percent for Run 1 and 100 percent for Run 2. Run 3 had nondetectable chromium levels at the SD/FF outlet, but inlet chromium samples were not collected during this run. Nickel removal by the SD/FF was low. Removal efficiencies were 22 and 5.6 percent. However, Run 3 had nondetectable nickel levels at the outlet.

Mercury was removed by the SD/FF at efficiencies of 60.7 to 99.7 percent, and an average efficiency of 86.3 percent. The lowest mercury removal efficiency and highest outlet concentration corresponded to the lowest inlet mercury concentration.

CDD/CDF for Mid-Connecticut data are presented in Table 7-15. Outlet CDD/CDF concentrations ranged from not detected to 1.39 ng/dscm at 7 percent $O_2$ over three runs and averaged 0.660 ng/dscm. The inlet CDD/CDF concentration ranged from 819 to 1,275 ng/dscm and averaged 1,019 ng/dscm. The corresponding removal efficiencies were at least 99.9 percent. The data show that the SD/FF at Mid-Connecticut, operating at 270$^0$F with inlet CDD/CDF concentrations as high as 1275 ng/dscm can achieve an outlet CDD/CDF concentration of less than 2 ng/dscm.

## TABLE 7-14. METALS EMISSIONS DATA FOR MID-CONNECTICUT

| Test Condition | Run Number | FF Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Inlet Concentration[a] (ug/dscm at 7% $O_2$) | | | | | | Outlet Concentration[b] ug/dscm at 7% $O_2$) | | | | | | Removal Efficiency (percent) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal | 1 | 274 | 0.0021 | 1,284 | 894 | 957 | 43,384 | 835 | 583 | ND[c] | NM[d] | 115 | ND | NM | 457 | 100 | -- | 88.0 | 100 | -- | 21.6 |
| SD/FF = Normal | 2 | 276 | 0.0041 | 838 | 1,241 | 895 | 31,387 | 1,181 | 499 | ND | NM | ND | ND | NM | 471 | 100 | -- | 100 | 100 | -- | 5.6 |
| | 3 | 278 | 0.0059 | NM | NM | NM | NM | NM | NM | ND | NM | ND | ND | NM | ND | -- | -- | -- | -- | -- | -- |
| Average | | 276 | 0.0040 | 1,061 | 1,068 | 921 | 37,386 | 1,008 | 541 | ND | NM | 38 | ND | -- | 309 | 100 | -- | 94.0 | 100 | -- | 13.6 |
| | 1 (Hg)[e] | 289 | NM | NM | NM | NM | NM | 331 | NM | NM | NM | NM | NM | 130 | NM | -- | -- | -- | -- | 60.7 | -- |
| | 2 (Hg)[e] | 278 | NM | NM | NM | NM | NM | 1,215 | NM | NM | NM | NM | NM | 4 | NM | -- | -- | -- | -- | 99.7 | -- |
| | 3 (Hg)[e] | 285 | NM | NM | NM | NM | NM | 1,107 | NM | NM | NM | NM | NM | 17 | NM | -- | -- | -- | -- | 98.4 | -- |
| Average (Hg tests) | | 284 | NM | NM | NM | NM | NM | 884 | NM | NM | NM | NM | NM | 50 | NM | -- | -- | -- | -- | 86.3 | -- |

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[a] Inlet metals samples for Runs 1, 2, 3 were collected using the draft EMSL metals method.

[b] Outlet metals samples for Runs 1, 2, 3 were collected using a combination Method 12/108.

[c] ND = not detected. Considered as zero in evaluating averages.

[d] NM = not measured.

[e] Additional inlet and outlet mercury samples were collected by Method 101A. Not measured simultaneously with other metals.

## TABLE 7-15. CDD/CDF DATA FOR MID-CONNECTICUT

| Test Condition | Run Number | FF Inlet Temperature (°F) | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (percent) |
|---|---|---|---|---|---|
| Combustor = Normal<br>SD/FF = Normal | 1 | 270 | 1,275 | 1.39 | 99.9 |
| | 2 | 266 | 819 | 0.59 | 99.9 |
| | 3 | 277 | 963 | ND[a] | 100 |
| Average | | 271 | 1,019 | 0.66 | 99.9 |

[a] ND = not detected. Considered as zero in evaluating averages.

### 7.2.5 Marion County.[9-12]

The Marion County Solid Waste-to-Energy Facility in Brooks, Oregon, consists of two 275-ton/day, mass burn, waterwall Martin GmbH combustors. Each combustor is equipped with identical, Teller SD/FF systems. The flue gases leave the boiler economizer and enter a cyclonic separator that removes large particles before entering the bottom of the SD. Slaked pebble lime is mixed with water and injected into the SD through an array of five two-fluid nozzles. The lime slurry feed rate is varied to maintain the SD outlet temperature between 260 and 300°F. The dry lime feed rate is approximately 425 lb/hr per unit. The lime concentration in the slurry is maintained at a rate sufficient to yield a stoichiometric ratio of lime to HCl of about 2 to 2.5. Tesisorb® is injected into the flue gas through a venturi located immediately before the FF inlet gas plenum to enhance collection performance and reduce pressure drop across the FF. The Amertherm reverse-air FF consists of six compartments of 120 fiberglass bags each. The net air-to-cloth ratio is 2.3 acfm/ft$^2$ at a flue gas flow of about 60,000 acfm. After exiting the FF, the combustion gases are discharged through a 258-foot high stack.

Three test programs have been conducted at Marion County. The first test program, conducted in September and October 1986, included compliance testing at the Unit 1 SD/FF outlet funded by the facility, and simultaneous testing at the SD/FF inlet funded by EPA. At the inlet and outlet of the SD/FF, flue gas was analyzed for CDD/CDF, PM, HCl, $SO_2$, and metals (lead, cadmium, chromium, and nickel) for three runs. A second program was conducted in February 1987. During these tests, $SO_2$ and CDD/CDF samples were collected at the SD/FF inlet.

The third test program was conducted in June 1987 on Unit 1 with funding from EPA. These tests focused on parametric testing of the combustor and SD/FF. The purposes of the test relative to the SD/FF were (1) to determine the removal of CDD/CDF by a SD/FF at combustor startup and shutdown conditions, (2) to evaluate acid gas removal efficiency as a function of temperature and stoichiometric ratio, and (3) to evaluate the performance of the SD/FF over the normal operating range of the combustor.

The combustor parameters which were varied during testing included steam load, excess air, and combustion air distribution. During the 11 runs with variations in combustor operation, the SD/FF was maintained at normal conditions. For the three SD/FF parametric tests, the SD outlet temperature was varied while the combustor was maintained at normal conditions. Flue gas was sampled at the SD/FF inlet and outlet using continuous emission monitors for HCl, $SO_2$, $NO_x$, THC, and CO. Continuous measurements of HCl and $SO_2$ were also taken at the SD outlet. For the shutdown and startup tests, flue gas was analyzed for CDD/CDF at the SD/FF inlet and outlet.

Acid gas data collected during the compliance and parametric test programs are presented in Table 7-16. During normal combustor and SD/FF operation (1986), outlet $SO_2$ concentrations ranged from 7.8 to 65.5 ppm at 7 percent $O_2$ and averaged 31.3 ppm. The $SO_2$ removal efficiency during these runs ranged from 73.8 to 93.3 percent and averaged 85.2 percent. During normal combustor and SD/FF operation, outlet HCl concentrations ranged from 4.09 to 42.4 ppm at 7 percent $O_2$ and averaged 17.7 ppm. Removal efficiencies for HCl ranged from 93.0 to 99.3 ppm during these runs and averaged 97.0 ppm.

During parametric testing of the combustor with normal SD/FF operation (1987), outlet $SO_2$ concentrations ranged from 9.9 to 386 ppm at 7 percent $O_2$. The corresponding $SO_2$ removal efficiencies were between 32 and 92 percent. Outlet HCl concentrations during parametric testing ranged from 11.5 to 84 ppm at 7 percent $O_2$. The corresponding HCl removal efficiencies were between 87 and 98 percent. These results show some differences from the 1986 compliance tests. The average outlet $SO_2$ concentration from the 1987 tests are approximately five times the value for the 1986 tests, while the average outlet HCl concentration is approximately three times as high. The removal efficiencies for both $SO_2$ and HCl are higher during the 1986 tests. These differences are probably a result of two times higher inlet $SO_2$ concentrations during the 1987 tests and the inability of the spray dryer to control these high inlet levels. A waste screening program is now used to remove materials causing high inlet $SO_2$ levels prior to being

TABLE 7-16. ACID GAS DATA FOR MARION COUNTY

| Test Conditions | Run Number | FF Inlet Temperature (°F) | Stoichiometric Ratio | Acid Gas Concentrations (ppmv, dry at 7% $O_2$) | | | | | | Acid Gas Removal Efficiency (percent) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Inlet | | Midpoint | | Outlet | | SD | | FF | | Overall | |
| | | | | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl |
| Combustor = Normal | 1 | 270 | 2.5 | 117 | 555 | NM[a] | NM | 8 | 4.1 | -- | -- | -- | -- | 93.3 | 99.3 |
| SD/FF = Normal (1986) | 2 | 272 | 2.1 | 181 | 555 | NM | NM | 21 | 6.7 | -- | -- | -- | -- | 88.5 | 98.9 |
| | 3 | 272 | 1.9 | 250 | 603 | NM | NM | 66 | 42.4 | -- | -- | -- | -- | 73.8 | 93.0 |
| Average | | 271 | 2.2 | 183 | 571 | NM | NM | 31 | 17.7 | -- | -- | -- | -- | 85.2 | 97.0 |
| Combustor = Parametric | 1 | 300 | 1.0 | 566 | 654 | 448 | 224 | 386 | 84.3 | 20.9 | 65.8 | 13.8 | 62.3 | 31.8 | 87.1 |
| SD/FF = Normal (1987) | 2 | 300 | 1.3 | 315 | 674 | 131 | 187 | 104 | 36.5 | 58.3 | 72.2 | 20.9 | 80.5 | 67.0 | 94.6 |
| | 3A | 300 | 1.2 | 428 | 495 | 305 | 183 | 203 | 54.6 | 28.6 | 63.0 | 33.5 | 70.2 | 52.5 | 89.0 |
| | 3B | 299 | 1.1 | 523 | 704 | 384 | 175 | 264 | 53.1 | 26.6 | 75.1 | 31.7 | 69.8 | 49.6 | 92.5 |
| | 4 | 301 | 1.9 | 119 | 639 | 30 | 150 | 10 | 11.5 | 75.1 | 76.6 | 66.5 | 92.3 | 91.6 | 98.2 |
| | 5 | 299 | 1.1 | 424 | 727 | 238 | 106 | 168 | 48.6 | 43.9 | 85.4 | 29.1 | 54.3 | 60.3 | 93.3 |
| | 6A | 302 | 1.4 | 335 | 683 | 230 | 225 | 197 | 74.4 | 28.2 | 67.1 | 17.9 | 66.9 | 41.1 | 89.1 |
| | 6B | 300 | 2.1 | 277 | 629 | 115 | 90 | 58 | 30.2 | 58.4 | 85.7 | 49.9 | 66.4 | 79.2 | 95.2 |
| | 7 | 288 | 1.6 | 288 | 670 | 205 | 222 | 148 | 71.4 | 29.0 | 66.8 | 27.8 | 67.9 | 48.7 | 89.3 |
| | 8 | 298 | 2.4 | 215 | 581 | 158 | 186 | 95 | 42.9 | 26.5 | 68.0 | 39.8 | 76.9 | 55.8 | 92.6 |
| | 9 | 299 | 2.2 | 171 | 654 | 39 | 196 | 23 | 21.0 | 77.3 | 70.0 | 41.2 | 89.3 | 86.6 | 96.8 |
| Average | | 299 | 1.6 | 333 | 646 | 207 | 177 | 151 | 48.0 | 43.0 | 72.3 | 33.8 | 72.4 | 60.4 | 92.5 |
| Combustor = Normal<br>SD/FF = Low SD outlet temperature (250°F) | 10 | 262 | 1.1 | 397 | 845 | 322 | 178 | 110 | 21.9 | 18.8 | 78.9 | 65.8 | 88.3 | 72.3 | 97.5 |
| Combustor = Normal<br>SD/FF = High SD outlet temperature (330°F) | 11A | 330 | 1.1 | 481 | 735 | 533 | 301 | 493 | 160 | -10.7 | 59.0 | 7.5 | 46.8 | -2.4[b] | 78.2 |
| Combustor = Normal<br>SD/FF = Very high SD outlet temp. (360°F) | 11B | 360 | 1.6 | 129 | 817 | 179 | 315 | 167 | 217 | -38.9 | 61.4 | 6.5 | 31.1 | -29.9[b] | 73.4 |

[a] NM = not measured.

[b] Negative removal efficiencies indicative of little or no $SO_2$ removal.

combusted. Another factor may have been that the 1986 tests were conducted at slightly lower FF inlet temperatures (270 versus 300°F), as discussed later.

The spray dryer parametric tests were performed to evaluate the effect of FF inlet temperature on performance. Run 10 was conducted at a very low FF inlet temperature (250°F). Outlet $SO_2$ concentration was 110 ppm for a removal efficiency of 72 percent. Outlet HCl concentration was 22 ppm for a removal efficiency of 97.5 percent. Runs 11A and 11B were conducted at elevated FF inlet temperatures (330 and 360°F, respectively). Outlet $SO_2$ concentrations were 490 and 170 ppm, but both tests indicated approximately zero removal efficiencies. Outlet HCl concentrations were 160 and 220 ppm, for removal efficiencies of 78 and 73 percent, respectively, at 330 and 360°F. Removal efficiencies for both $SO_2$ and HCl were lower during the elevated FF inlet temperature tests as compared to normal SD operations.

Increasing stoichiometric ratio increased removal efficiency for both $SO_2$ and HCl, as shown in Figure 7-3 and 7-4, respectively. However, because the lime feed rate was measured as the total feed to both units and because the two units were not always operating identically, different lime feed rates may have been supplied to the units. Thus, the calculated stoichiometric ratios (based on the assumption of equal lime flow to each unit) are only estimates. Calculated stoichiometric ratios varied from 1.9 to 2.5 during the 1986 tests, 1.0 to 2.4 during the combustor parametric tests, and 1.1 to 1.6 during the SD parametric tests. The scatter in the data are probably due to effects of temperature and inaccuracy in calculating the stoichiometric ratio.

The effect of FF inlet temperature on SD/FF performance is apparent at Marion County. At FF inlet temperatures of 330 and 360°F, during runs 11A and 11B, the lowest $SO_2$ and HCl removal efficiencies were observed. At 260 to 270°F, during run 10 of the parametric testing and all three runs of compliance testing, the highest $SO_2$ and HCl removal efficiencies were observed. At approximately 300°F during the 11 parametric combustor conditions, acid gas removal efficiencies varied between 32 and 92 percent

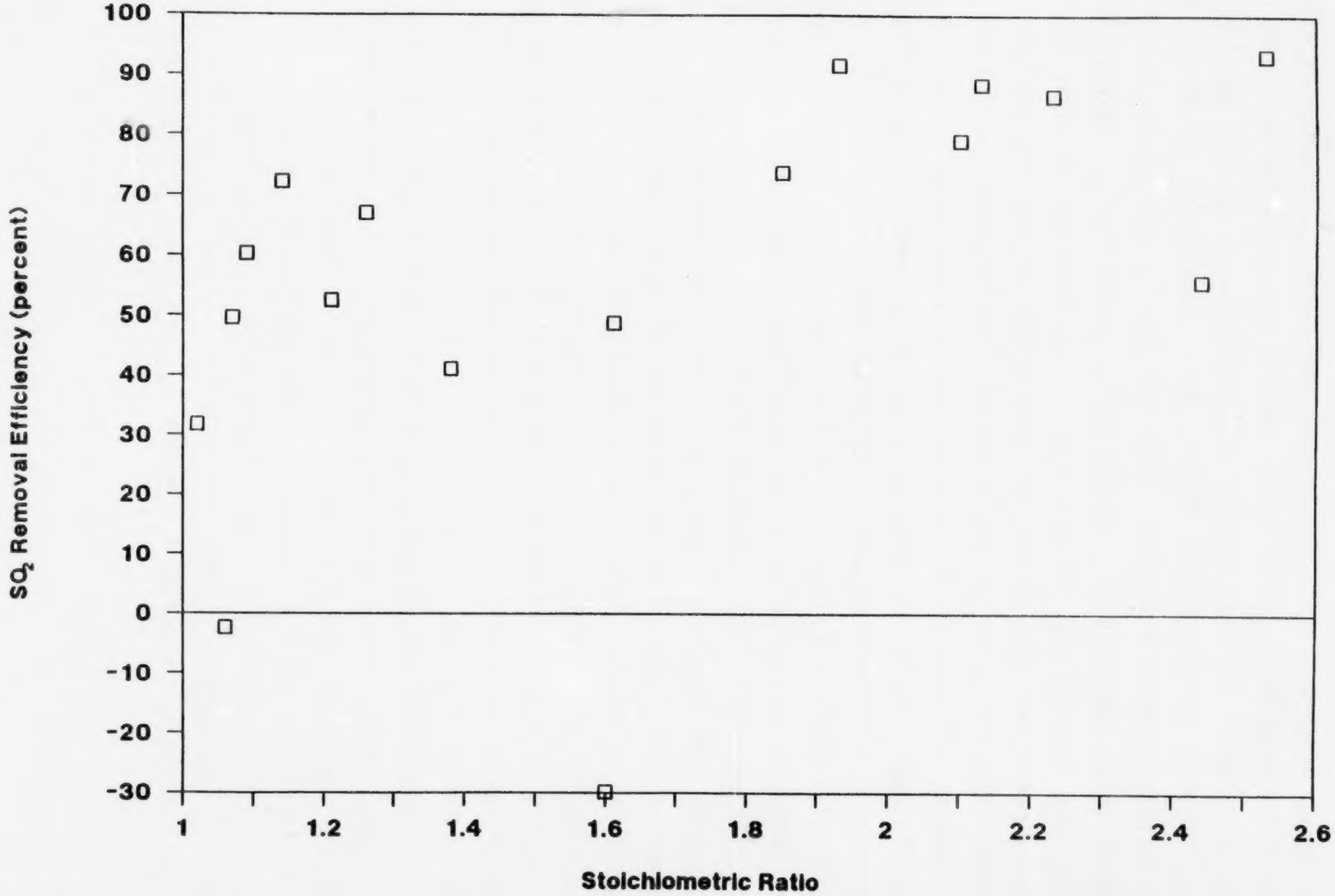


Figure 7-3. $SO_2$ removal efficiency as a function of stoichiometric ratio at Marion County.

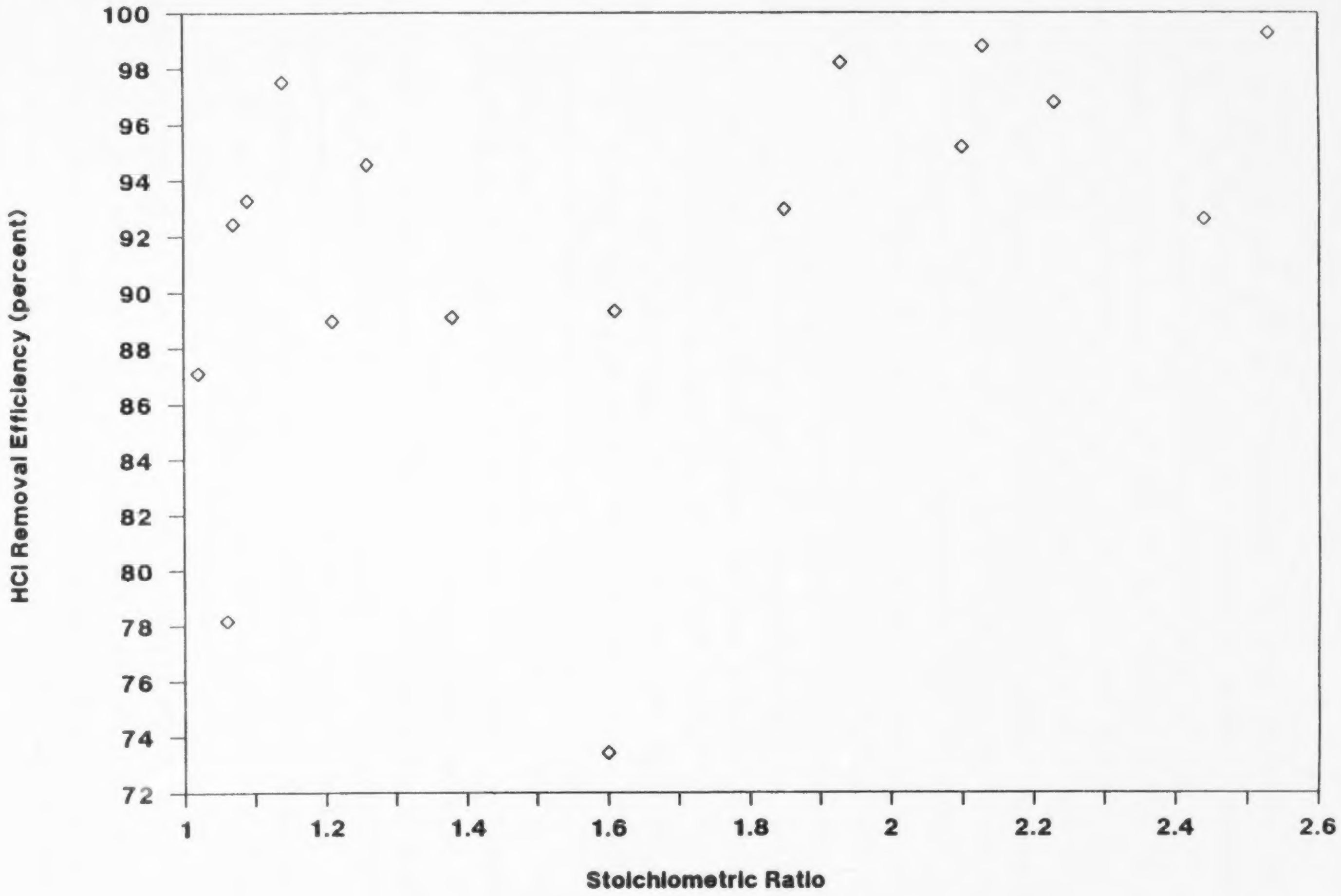


Figure 7-4. HCl removal efficiency as a function of stoichiometric ratio at Marion County.

for $SO_2$ and between 87 and 98 percent for HCl. The average removal efficiencies for this temperature were 60 percent for $SO_2$ and 93 percent for HCl.

The effect of inlet $SO_2$ concentration on $SO_2$ and HCl removal efficiencies is shown in Figures 7-5 and 7-6, respectively, for all the tests. For both $SO_2$ and HCl, removal efficiency increased with decreasing inlet $SO_2$ concentration. This trend is less apparent for HCl removal efficiency because HCl will react with the available lime generally before $SO_2$ does, and thus is less prone to be affected by increases in inlet $SO_2$ concentration. Below inlet $SO_2$ concentrations of 200 ppm, $SO_2$ and HCl removal efficiencies were at least 87 and 97 percent, respectively.

In Figure 7-7, the relationship between $SO_2$ and HCl removal efficiency is shown for all runs. There is an approximately linear relationship between the two values. At $SO_2$ removal efficiencies of 90 percent or higher, HCl removal efficiency is at least 98 percent.

During the combustor parametric tests with normal SD operation, 20 to 80 percent $SO_2$ removal occurred across the SD with an additional 15 to 60 percent removal across the FF. The $SO_2$ removal was similar at the low FF inlet temperature run, but at the high temperature runs, no removal occurred across the SD or FF. For HCl, about 65 to 90 percent removal occurred across both the SD and FF during normal and low temperature operation. However, at the high FF inlet temperature tests, approximately 60 percent HCl removal occurred across the SD and an additional 30 to 45 precent removal occurred across the FF.

PM data are presented for the 1986 compliance testing in Table 7-17. Outlet PM concentrations ranged from 0.0013 to 0.0037 gr/dscf at 12 percent $CO_2$ over six runs and averaged 0.0023 gr/dscf. The corresponding PM removal efficiencies for the three runs with simultaneous inlet and outlet data were between 99.6 and 99.8 percent and averaged 99.7 percent. The net air-to-cloth ratio was 2.4 acfm/$ft^2$, or less during the tests conducted.

Metals data are presented for the 1986 testing in Table 7-18. Removal efficiencies measured over the course of three test runs for cadmium, chromium, and lead were all greater than 99.7 percent. Nickel removal efficiency was measured at 50 percent. Mercury emissions at the FF outlet are lower than typical uncontrolled values, suggesting a removal efficiency

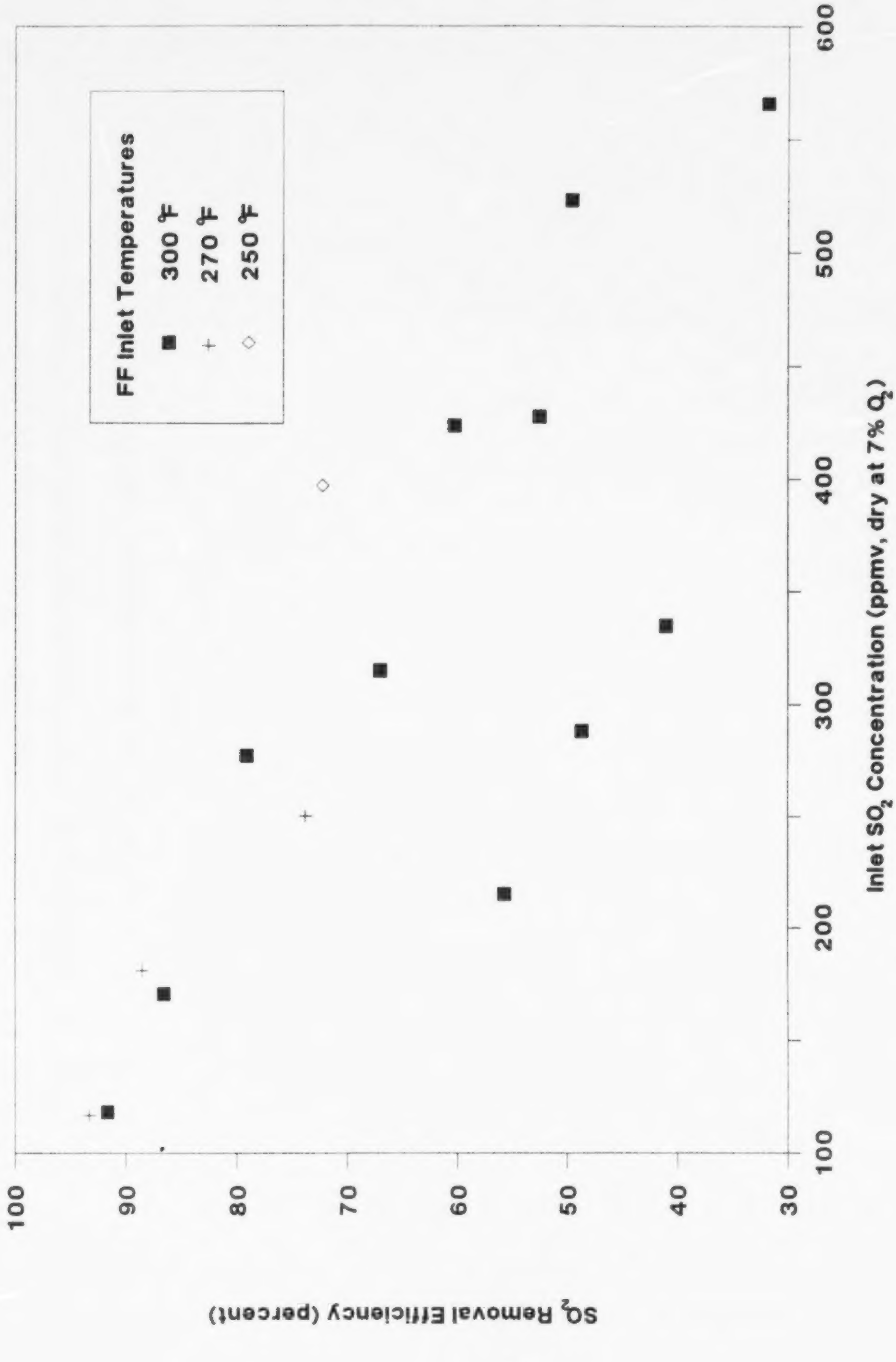


Figure 7-5. SO$_2$ removal efficiency as a function of inlet SO$_2$ concentration at Marion County.

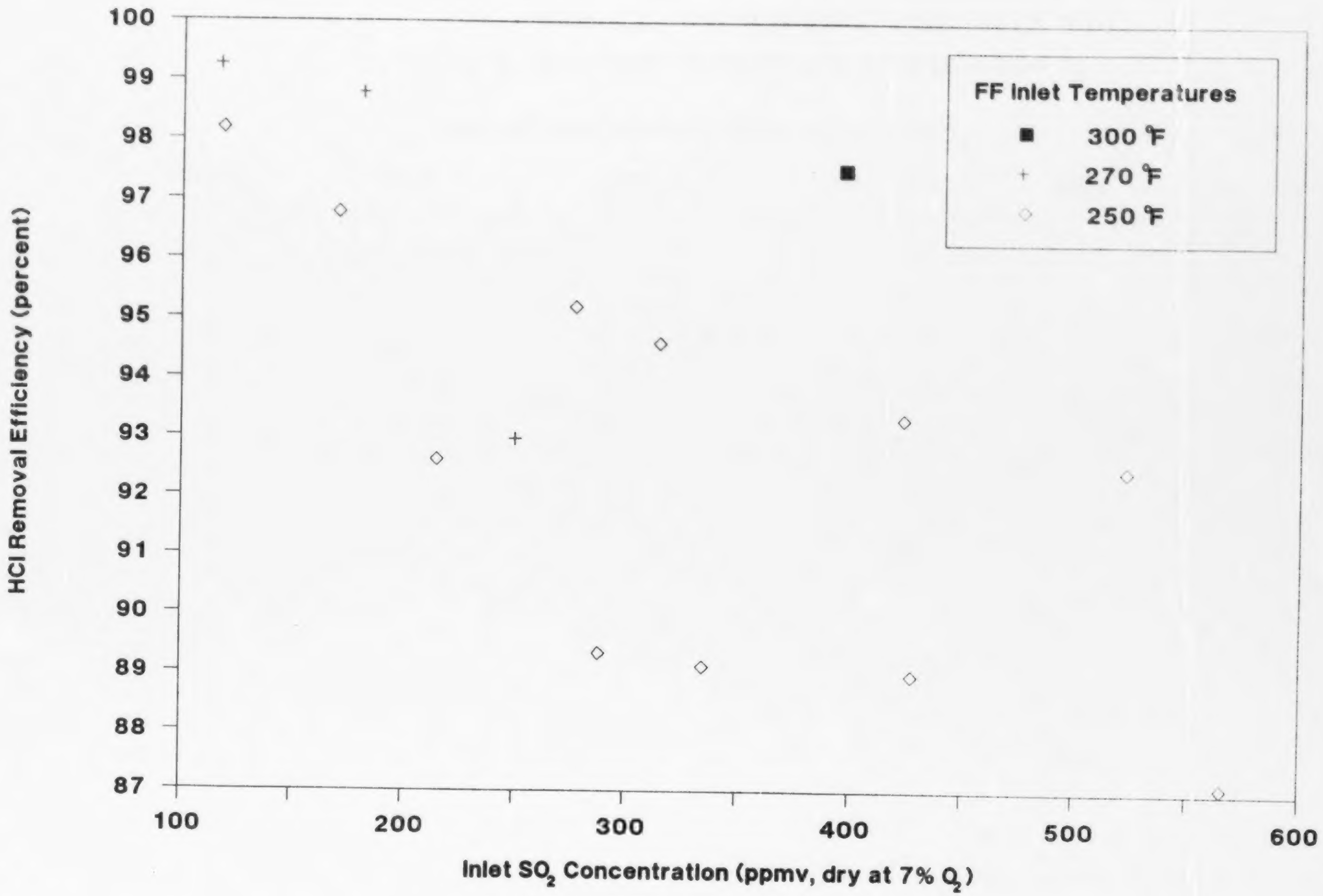


**Figure 7-6.** HCl removal efficiency as a function of inlet $SO_2$ concentration at Marion County.

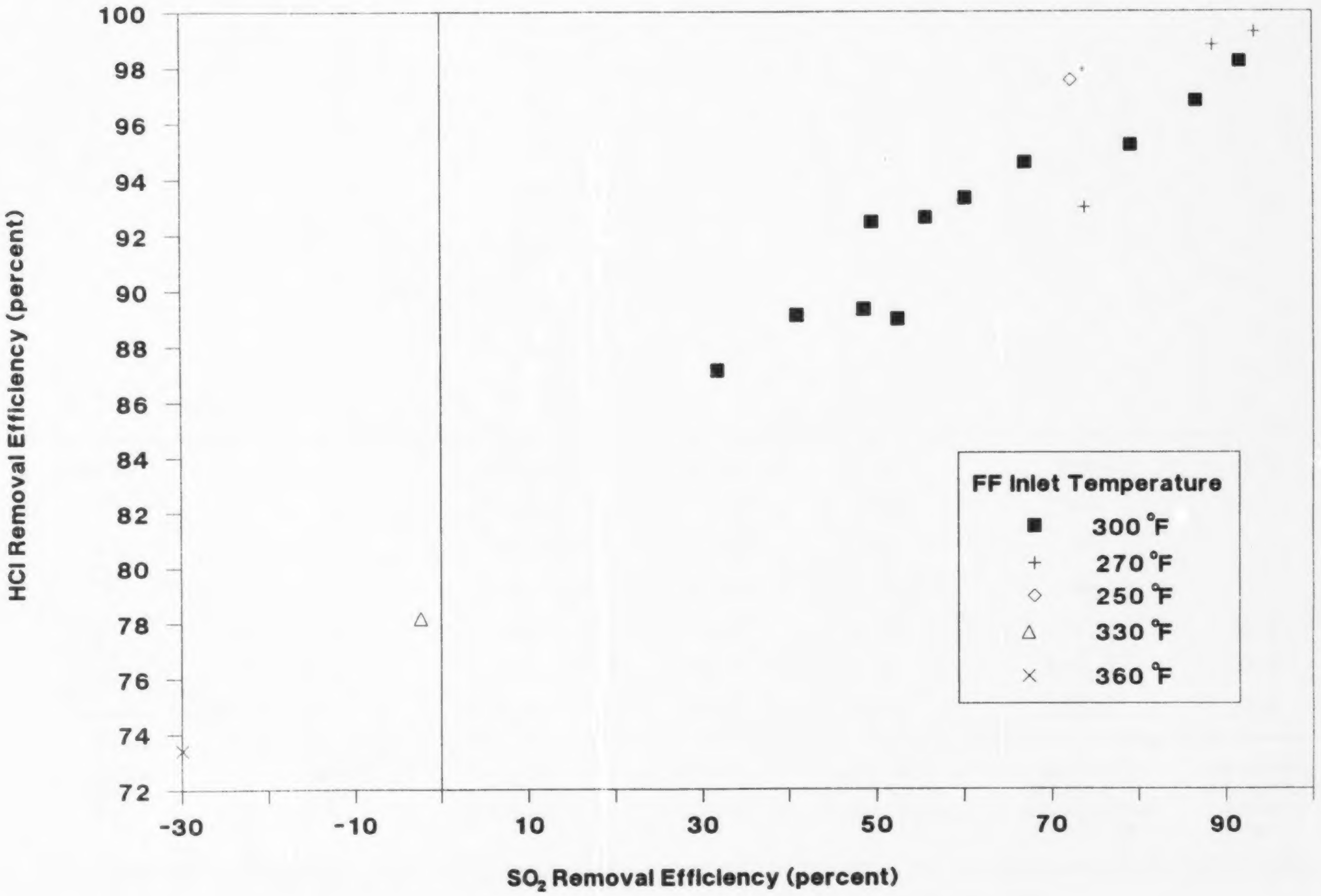


Figure 7-7. HCl removal efficiency as a function of $SO_2$ removal efficiency at Marion County.

TABLE 7-17. PARTICULATE DATA FOR MARION COUNTY

| Test Condition | Run Number | FF Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at (12% $CO_2$) | Outlet PM Concentration (gr/dscf at (12% $CO_2$) | PM Removal Efficiency (percent) |
|---|---|---|---|---|---|---|
| Combustor = Normal<br>SD/FF = Normal<br>(1986) | 1 | 270 | 63,098 | 1.05 | 0.0037 | 99.6 |
| | 2 | 272 | 58,123 | 1.12 | 0.0018 | 99.8 |
| | 3 | 272 | 57,029 | 0.740 | 0.0013 | 99.8 |
| | 4 | 271 | 59,921 | 0.848 | NM[a] | -- |
| | 5 | 272 | 61,970 | 0.791 | NM | -- |
| | 6 | 272 | 57,476 | 0.739 | NM | -- |
| Average | | 272 | 59,603 | 0.881 | 0.0023 | 99.7 |

[a] NM = not measured.

TABLE 7-18. METALS EMISSIONS DATA FOR MARION COUNTY

| Test Condition | Run Number | FF Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Inlet Concentration$^{a}$ (ug/dscm at 7% $O_2$) | | | | | Outlet Concentration$^{b}$ (ug/dscm at 7% $O_2$) | | | | | Removal Efficiency (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Cd | Cr | Pb | Hg | Ni | Cd | Cr | Pb | Hg | Ni | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal<br>SD/FF = Normal<br>(1986) | 4 | 271 | -- | 1,180 | 464 | 16,800 | NM$^{a}$ | 16.9 | 18$^{b}$ | ND$^{b,c}$ | 190$^{b}$ | 228$^{d}$ | 1.6$^{b}$ | 98.1 | 100 | 98.6 | -- | 89.7 |
| | 5 | 272 | -- | 1,210 | 269 | 19,900 | NM | 4.6 | 2.9 | 0.13 | 15 | 298 | 3.1 | 99.7 | 99.9 | 99.9 | -- | 23.0 |
| | 6 | 272 | -- | 973 | 533 | 24,800 | NM | 15.7 | 2.3 | 0.20 | 22 | 192 | 3.1 | 99.7 | 99.9 | 99.9 | -- | 77.4 |
| Average | | 272 | 0.0023$^{e}$ | 1,121 | 422 | 20,500 | NM | 12.4 | 2.6$^{f}$ | 0.17$^{f}$ | 19$^{f}$ | 239 | 3.1$^{f}$ | 99.7$^{f}$ | 99.9$^{f}$ | 99.9$^{f}$ | -- | 50.2$^{f}$ |

[a] NM = not measured.

[b] Fabric filter was by-passed during the test run for five minutes. Emissions measured are higher than normally expected.

[c] ND = not detected. Considered as zero in evaluating average.

[d] Mercury measured at different times than other metals. Results not affected by the by-pass of the fabric filter.

[e] Particulate results not collected simultaneously. Average result given from same test program.

[f] Average outlet concentrations and removal efficiencies include results from Runs 2 and 3 only.

of approximately 50 percent. However, because inlet mercury concentrations are highly variable, the actual mercury removal efficiency may differ.

In Table 7-19, CDD/CDF data are presented for the 1986 runs and transient condition tests. During normal operation of the combustor and SD/FF, outlet CDD/CDF concentrations for Runs 2 and 3 were 1.86 and 0.665 ng/dscm at 7 percent $O_2$ and averaged 1.26 ng/dscm. Sample recovery problems prevented analysis of the Run 1 sample. The inlet CDD/CDF concentration was 43 ng/dscm for one run, but sample recovery difficulties prevented analysis of Runs 1 and 3. The resulting removal efficiency was 96 percent.

During shutdown, inlet CDD/CDF concentrations of 85 and 38 ng/dscm were measured for two samples collected simultaneously except the second train did not include a sootblowing. The outlet CDD/CDF concentrations were 3.1 and 0.81 ng/dscm for two samples collected over the entire test, including the sootblowing. The removal efficiency was 97 percent based on the averages of the inlet and outlet concentrations.

During startup, two sample trains were run at the inlet consecutively over the first and second halves of the 4-hour test. Two concurrent samples were collected over the full test at the outlet. At the inlet, the CDD/CDF concentration was 710 ng/dscm during the first half of the test and 160 ng/dscm for the second half of the test. The only outlet sample which could be analyzed had a CDD/CDF concentration of 3.4 ng/dscm. Based on the average of the inlet samples and the single outlet sample, the CDD/CDF removal efficiency was 99 percent.

CDD/CDF emissions were consistently low despite wide variations in inlet CDD/CDF concentrations (38 to 712 ng/dscm). Thus, the SD/FF at Marion County, with inlet CDD/CDF concentrations of 38 to 712 ng/dscm, can achieve outlet CDD/CDF levels of less than 3.4 ng/dscm.

### 7.2.6 Penobscot[13,14]

The Penobscot Energy Recovery Facility in Orrington, Maine consists of two 360-ton/day RDF-fired boilers manufactured by Riley Stoker. Each boiler produces 66,700 lb/hr of steam. Flue gas emissions from each unit are controlled by a spray dryer/fabric filter system supplied by General Electric Environmental Services. Lime slurry is injected into the spray

TABLE 7-19. CDD/CDF DATA FOR MARION COUNTY

| Test Condition | Run Number | FF Inlet Temperature | Inlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) | CDD/CDF Removal Efficiency (%) |
|---|---|---|---|---|---|
| 1986 TESTS | | | | | |
| Combustor = Normal | 2 | 272 | 43.0 | 1.86 | 95.7 |
| SD/FF = Normal | 3 | 272 | NR[a] | 0.665 | -- |
| Average | | 272 | 43.0 | 1.26 | 95.7 |
| 1987 TESTS | | | | | |
| Combustor = Shutdown[b] | 1A[b] | 293 | 84.9 | 3.01 | 96.9[c] |
| SD/FF = Normal | 1B[b] | 293 | 38.3 | 0.806 | |
| Combustor = Startup | 1A[d] | 301 | 712 | 3.36 | 99.2[e] |
| SD/FF = Normal | 1B[d] | 301 | 158 | NR | |

[a] NR = not reported. Analytical difficulties encountered with the sample.

[b] Shutdown test had two trains at inlet and two trains at outlet. Inlet Train A included a sootblowing and inlet Train B did not (1/2 hour difference in run length). The two outlet train samples were collected over the full test.

[c] Removal efficiency calculated based on average inlet concentration for two trains and average outlet concentration from two trains.

[d] Start-up test had two trains at inlet and two trains at outlet. Inlet Train A was for the first two hours of the 4-hour test and inlet Train B was run for the last two hours. The two outlet trains were used over the full test.

[e] Removal efficiency was calculated based on average of two inlets and one outlet concentrations.

dryer through a rotary atomizer. Flue gases exiting the spray dryer enter a pulse-jet fabric filter for PM control. The design flue gas flow at the FF inlet is 170,000 acfm at 300°F. The FF has six modules of 126 bags each. The design PM removal efficiency is 99.8 percent to achieve outlet PM levels of 0.01 gr/dscf at 12 percent $CO_2$.

In August 1988, a compliance test was conducted at the facility. The combustor and SD/FF were operated normally during testing. At the SD/FF outlet, flue gas was sampled and analyzed for $SO_2$, HCl, PM, metals (cadmium, chromium, and lead), and CDD/CDF. No measurements were made at the SD inlet.

Acid gas data are presented in Table 7-20. Outlet $SO_2$ concentrations ranged from 7.65 to 13.0 ppm at 7 percent $O_2$ over three runs and averaged 11.1 ppm. Outlet HCl concentrations ranged from 1.06 to 1.42 ppm at 7 percent $O_2$ and averaged 1.18 ppm. The FF inlet temperatures was a consistent 296°F.

PM data are presented in Table 7-21. Outlet PM concentrations ranged from 0.00058 to 0.0015 gr/dscf at 12 percent $CO_2$ over three runs and averaged 0.0011 gr/dscf. The flue gas flow rate, averaging 172,600 acfm for the three test runs, was very near the design rate of 170,000 acfm. At this flue gas flow rate, the FF exceeded its design performance level of 0.01 gr/dscf.

Metals emissions data are presented in Table 7-22. Sampling for cadmium, chromium, and lead was conducted simultaneously with PM sampling. Based on typical uncontrolled metals concentrations, removal efficiencies for cadmium, chromium, and lead were all greater than 99.8 percent.

In Table 7-23, CDD/CDF data are presented. Outlet CDD/CDF concentrations ranged from not detected to 3.87 ng/dscm over three runs and averaged 2.39 ng/dscm. Inlet CDD/CDF concentrations were not measured. Nevertheless, at a consistent FF inlet temperature of 295°F, the SD/FF system at Pensobscot demonstrated outlet CDD/CDF levels of less than 4 ng/dscm.

### 7.2.7 Quebec City[15]

The Quebec City, Canada, municipal waste combustion facility consists of four separate mass burn, waterwall combustors. The combustors were

## TABLE 7-20. ACID GAS DATA FOR PENOBSCOT

| Test Conditions | Run Number | FF Inlet Temperature[a] ($^oF$) | Outlet Acid Gas Concentration (ppmv, dry at 7% $O_2$) $SO_2$ | HCl |
|---|---|---|---|---|
| Combustor = Normal | 1 | 296 | 13.0 | 1.1 |
| SD/FF = Normal | 2 | 297 | 12.7 | 1.4 |
| | 3 | 296 | 7.7 | 1.1 |
| Average | | 296 | 11.1 | 1.2 |

[a] Temperature estimated from measured value at the stack and an assumed temperature drop across the fabric filter ($10^oF$).

## TABLE 7-21. PARTICULATE DATA FOR PENOBSCOT

| Test Condition | Run Number | FF Inlet Temperature[a] ($^oF$) | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1 | 296 | 175,700 | 0.0011 |
| SD/FF = Normal | 2 | 297 | 172,200 | 0.00058 |
| | 3 | 296 | 169,800 | 0.0015 |
| Average | | 296 | 172,600 | 0.0011 |

[a] Temperature estimated from measured value at the stack and an assumed temperature drop across the fabric filter ($10^oF$).

## TABLE 7-22. METALS DATA FOR PENOBSCOT

| Test Condition | Run Number | FF Inlet Temperature[a] (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) | | |
|---|---|---|---|---|---|---|
| | | | | Cd | Cr | Pb |
| Combustor = Normal<br>SD/FF = Normal | 1 | 296 | 0.0011 | 0.57 | 2.38 | 6.9 |
| | 2 | 294 | 0.00058 | 1.33 | 2.15 | 19.1 |
| | 3 | 295 | 0.0015 | 0.85 | 1.98 | 6.8 |
| Average | | 295 | 0.0011 | 0.92 | 2.17 | 11.0 |

[a] Temperature estimated from measured value at the stack and an assumed temperature drop across the fabric filter (10°F).

TABLE 7-23. CDD/CDF DATA FOR PENOBSCOT

| Test Condition | Run Number | FF Inlet Temperature[a] (°F) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1 | 295 | 3.29 |
| SD/FF = Normal | 2 | 296 | 3.87 |
| | 3 | 295 | ND[b] |
| Average | | 295 | 2.39 |

---

[a] Temperature estimated from measured value at the stack and an assumed temperature drop across the fabric filter (10°F).

[b] ND = not detected.

originally built in 1975 with Von Roll reciprocating grates. Waterwall arches were added to each combustion chamber in 1979. Each unit is designed to combust 250 tons/day of MSW. Emissions were originally controlled by 2-field ESP's.

Environment Canada, in cooperation with Flakt Canada, Ltd., established an extensive test program to evaluate the capability of a pilot-scale SD/FF control system to remove PM, $SO_2$, HCl, heavy metals, CDD/CDF, and other organic compounds. Flakt constructed a pilot-scale SD/FF facility at the Quebec City plant equipped with:

(1) a flue gas slipstream from the ESP inlet of Unit 3 to deliver 2,000 $ft^3$/min at $500^oF$ to the pilot facility;

(2) a SD vessel with a two-fluid nozzle for injecting a lime slurry and a bottom screw conveyor for removing ash; and

(3) a pulse-cleaned FF using high-temperature teflon bags with an air-to-cloth ratio of 4.4 acfm/$ft^2$. Ash from the FF could be recirculated to the SD for reinjection with fresh slurry.

Testing was conducted with the pilot-scale SD/FF system in March 1985. Results from other tests at Quebec City during the same test program are presented in Section 5.2. These tests were conducted using a dry sorbent injection system with the same FF at various FF inlet temperatures. In Section 2.2.1.9, results from testing of the Quebec City combustor with the existing ESP are presented. The combustor was operated under normal conditions throughout testing of the pilot-scale SD/FF system. The SD/FF was operated with and without FF ash recycle, two test runs at each condition, and at a single SD outlet temperature of $285^oF$. Flue gas was sampled at the SD inlet, SD outlet, and FF outlet for PM, HCl, $SO_2$, metals (arsenic, cadmium, chromium, mercury, lead, and nickel), CDD/CDF, and other organics. PM and metals data were not taken at the mid-point sampling location.

Acid gas data are presented in Table 7-24. Outlet $SO_2$ concentrations ranged from 31.3 to 61.0 ppm at 7 percent $O_2$ for the four test runs. The average removal efficiencies for $SO_2$, with and without fly ash recycle, were 61 and 66 percent, respectively, yielding corresponding outlet emissions of

TABLE 7-24. ACID GAS DATA FOR QUEBEC CITY PILOT SD/FF

| Test Condition | Run Number | FF Inlet Temperature (°F) | Stoichiometric Ratio | Acid Gas Concentrations (ppmv, dry at 7% $O_2$) | | | | | | Acid Gas Removal Efficiency (percent) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Inlet | | Midpoint | | Outlet | | SD | | FF | | Overall | |
| | | | | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl | $SO_2$ | HCl |
| Combustor = Normal | 7 | 280 | 1.5 | 128 | 338 | 76.7 | 148 | 33.9 | 27.8 | 40.2 | 56.4 | 55.8 | 81.2 | 73.5 | 91.8 |
| SD/FF = Normal | 8 | 283 | 1.4 | 100 | 354 | 67.7 | 173 | 41.5 | 34.7 | 23.5 | 51.1 | 38.7 | 80.0 | 58.6 | 90.2 |
| No ash recycle | | | | | | | | | | | | | | | |
| Average | | 282 | 1.5 | 114 | 346 | 72.2 | 161 | 37.7 | 31.3 | 31.9 | 53.8 | 47.3 | 80.6 | 66.1 | 91.0 |
| Combustor = Normal | 9 | 285 | 1.3 | 101 | 461 | 63.1 | 152 | 31.3 | 35.0 | 37.7 | 67.1 | 50.5 | 77.0 | 69.2 | 92.4 |
| SD/FF = Normal | 10 | 283 | 1.1 | 127 | 552 | 86.7 | 176 | 61.0 | 54.7 | 31.8 | 68.2 | 29.7 | 68.8 | 52.0 | 90.1 |
| With ash recycle | | | | | | | | | | | | | | | |
| Average | | 284 | 1.2 | 114 | 507 | 74.9 | 164 | 46.2 | 44.9 | 34.8 | 67.7 | 40.1 | 72.9 | 60.6 | 91.3 |

46 ppm and 38 ppm. Outlet HCl concentrations were between 27.8 and 54.7 ppm at 7 percent $O_2$. The HCl removal efficiency for both SD/FF operating conditions averaged 91.1 percent.

As shown in Figure 7-8, stoichiometric ratio had some effect on $SO_2$ removal efficiency. $SO_2$ removal efficiency generally increased with increasing stoichiometric ratio. For Runs 9 and 10, which had ash recycle, the actual stoichiometric ratio is somewhat higher than the value shown, depending on the amount of unreacted lime in the ash recycle. HCl removal efficiency was independent of stoichiometric ratio over the narrow range of stoichiometric ratios tested. Inlet $SO_2$ and HCl concentrations did not consistently affect performance.

Removal of $SO_2$ across the SD as well as across the FF was very similar with and without ash recycle. $SO_2$ removal across the SD at both conditions averaged 30 to 35 percent. $SO_2$ removal across the FF averaged about 40 to 45 percent. Although overall HCl removal efficiencies were nearly identical with and without ash recycle, HCl removal across the SD was higher with ash recycle (68 versus 54 percent). Conversely, HCl removal across the FF was higher without ash recycle (81 versus 73 percent). Whether these differences are because of the use of recycle or are due to normal variation of performance cannot be ascertained from the available data.

The use of ash recycle does not appear to significantly change performance relative to $SO_2$ and HCl. By using ash recycle, however, the amount of fresh sorbent required may be lessened.

In Table 7-25, particulate data are presented for the four performance tests as well as for four characterization tests performed prior to the performance tests. The characterization tests were used to familiarize testing personnel with the SD/FF system. It was determined during these tests that no particulate samples would be collected at the outlet during the performance tests because insufficient PM was collected for analysis. Of the four characterization tests, three yielded nondetectable amounts of PM (<0.0002 gr/dscf) and one had a concentration of 0.0018 gr/dscf.

Metals data are presented in Table 7-26. Greater than 99.9 percent of the arsenic, cadmium, chromium, lead, and nickel were removed across the SD/FF both with and without ash recycle. Removal efficiencies for mercury were consistently near 95 percent.

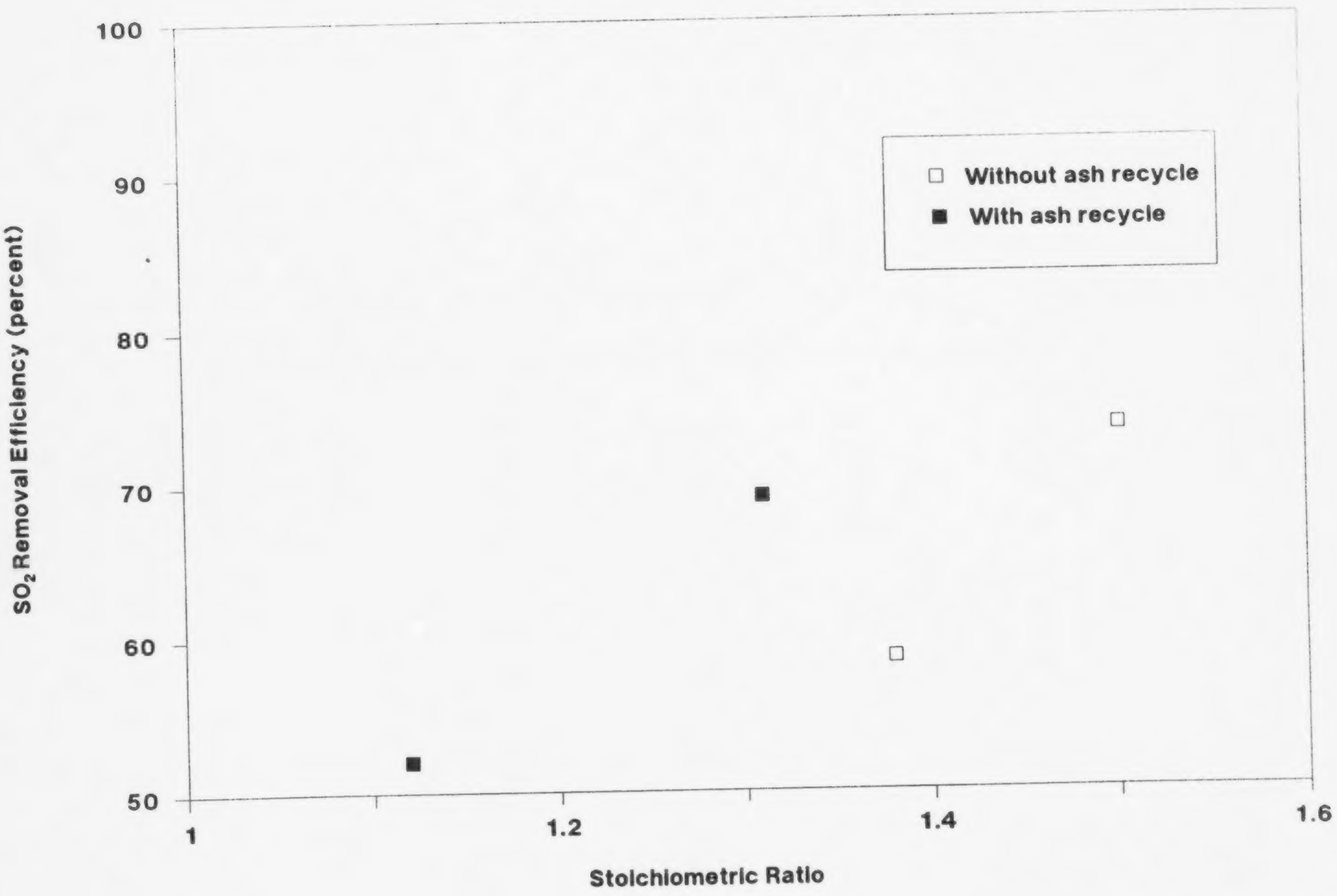


Figure 7-8. $SO_2$ removal efficiency as a function of stoichiometric ratio at Quebec City.

## TABLE 7-25. PARTICULATE DATA FROM QUEBEC CITY PILOT SD/FF

| Test Condition | Run Number | FF Inlet Temperature (°F) | Flue Gas Flow (acfm) | Inlet PM Concentration (gr/dscf at (12% $CO_2$) | Outlet PM Concentration (gr/dscf at (12% $CO_2$) | PM Removal Efficiency (percent) |
|---|---|---|---|---|---|---|
| Combustor = Normal SD/FF = Normal (284°F FF inlet temperature) | 7 | 281 | 4,115 | 2.43 | NM[a] | -- |
| | 8 | 283 | 4,213 | 2.61 | NM | -- |
| Average | | 282 | 4,164 | 2.52 | NM | -- |
| Combustor = Normal SD/FF = Ash Recycle (284°F FF inlet temperature) | 9 | 285 | 4,125 | 3.33 | NM | -- |
| | 10 | 283 | 4,125 | 3.30 | NM | -- |
| Average | | 284 | 4,125 | 3.32 | NM | -- |
| Combustor = Normal SD/FF = Normal (302°F FF inlet temperature) | 6CT[c] | 290 | 3,565 | 1.61 | ND[b] | 100 |
| | 7CT | 286 | 3,591 | 1.99 | ND | 100 |
| | 8CT | 284 | 3,530 | 1.01 | 0.0018 | 99.8 |
| | 9CT | 291 | 3,589 | 1.84 | ND | 100 |
| Average | | 288 | 3,568 | 1.61 | 0.0005 | 99.9 |

[a] NM = not measured.

[b] ND = not detected. Considered as zero in evaluating averages.

[c] CT = characterization test.

TABLE 7-26. METALS EMISSIONS DATA FOR QUEBEC CITY PILOT SD/FF

| Test Condition | Run Number | FF Inlet Temperature (°F) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) | Inlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Outlet Concentration (ug/dscm at 7% $O_2$) | | | | | | Removal Efficiency (percent) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni | As | Cd | Cr | Pb | Hg | Ni |
| Combustor = Normal | 7 | 280 | -- | 84 | 1,207 | 1,320 | 25,520 | 139 | 686 | 0.05 | ND[a] | 0.44 | 2.4 | 6.1 | 1.84 | 99.94 | 100 | 100 | 100 | 95.6 | 100 |
| SD/FF = Normal | 8 | 283 | -- | 130 | 1,242 | 1,583 | 34,518 | 234 | 742 | 0.02 | ND | ND | ND | 13.9 | 0.80 | 99.98 | 100 | 100 | 100 | 94.1 | 99.9 |
| Average | | 282 | | 107 | 1,225 | 1,452 | 30,019 | 187 | 714 | 0.04 | ND | 0.22 | 1.2 | 10.0 | 1.32 | 99.96 | 100 | 100 | 100 | 94.9 | 99.9 |
| Combustor = Normal | 9 | 285 | -- | 138 | 1,187 | 1,575 | 36,548 | 331 | 3,937 | 0.06 | ND | 0.92 | 5.1 | 17.0 | 2.31 | 99.96 | 100 | 99.97 | 99.99 | 94.9 | 99.99 |
| SD/FF = Ash Recycle | 10 | 283 | -- | 117 | 1,117 | 1,760 | 31,377 | 388 | 1,102 | 0.01 | ND | 0.47 | 7.1 | 21.6 | 1.89 | 99.99 | 100 | 99.97 | 99.98 | 94.4 | 99.8 |
| Average | | 284 | | 128 | 1,152 | 1,668 | 33,963 | 360 | 2,520 | 0.04 | ND | 0.70 | 6.1 | 19.3 | 2.10 | 99.97 | 100 | 99.97 | 99.98 | 94.7 | 99.99 |

[a] ND = not detected. Considered as zero in evaluating averages.

CDD/CDF data for the pilot-scale SD/FF system are presented in Table 2-27. Outlet CDD/CDF concentrations were not detected for three of four runs and were 2.52 ng/dscm for Run 9 which had ash recycle. Because CDD/CDF was detected in only one run, the effects of inlet CDD/CDF and temperature cannot be evaluated. Very little CDD/CDF removal occurred across the SD at Quebec City. For three of four runs (two without recycle and one with ash recycle), the CDD/CDF removal efficiency across the SD was 10 to 14 percent. During Run 10, however, the CDD/CDF at the SD outlet was higher than at the SD inlet. This may be due to desorption of CDD/CDF from the recycled ash, but also may be within sampling and analytical error. These data indicate that the overall pilot-scale SD/FF system at Quebec City when operated 285°F was capable of outlet CDD/CDF concentrations less than 3 ng/dscm and that effective operation of the FF is essential for high levels of CDD/CDF reduction.

### 7.2.8 Stanislaus County[16,17]

The Stanislaus Waste-to-Energy Facility in Crows Landing, California consists of two identical Martin GmbH mass burn, waterwall combustors, each capable of combusting 400 ton/day MSW. Each combustor is equipped with Exxon's Thermal DeNO$_x$ system consisting of ammonia injection into the upper furnace for NO$_x$ control.

Emissions are controlled downstream of the boiler with a Flakt spray dryer/fabric filter system. In the SD, slaked lime slurry is injected through two-fluid nozzles, with the slurry feed rate controlled according to the stack $SO_2$ concentration and the dilution water flow controlled according to the SD outlet temperature. A residence time in the SD of 15 seconds is maintained to dry the slurry. Flue gas exiting the SD flows through the pulse-jet FF at 94,000 acfm and 285°F. The FF has six compartments of teflon-coated fiberglass bags (1,596 bags total) and a net air-to-cloth ratio of 3.2 acfm/ft$^2$.

In December 1988, compliance testing was conducted at the facility. The combustor and air pollution control system operated normally during testing. At the SD/FF outlet, flue gas was sampled for $SO_2$, HCl, PM, metals (arsenic, cadmium, chromium, lead, mercury, and nickel), CDD/CDF, and other organics. Nitrogen oxides were also measured to show performance of the

TABLE 7-27. CDD/CDF DATA FOR QUEBEC CITY PILOT SD/FF

| Test Condition | Run Number | FF Inlet Temperature (°F) | CDD/CDF Concentration (ng/dscm at 7% $O_2$) |  |  | CDD/CDF Removal Efficiency (percent) |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  | Inlet | Midpoint | Outlet | SD | FF | Overall |
| Combustor = Normal | 7 | 280 | 1,954 | 1,703 | ND[a] | 12.9 | 100 | 100 |
| SD/FF = Normal | 8 | 283 | 1,574 | 1,359 | ND | 13.7 | 100 | 100 |
| No ash recycle |  |  |  |  |  |  |  |  |
| Average |  | 282 | 1,764 | 1,531 | ND | 13.3 | 100 | 100 |
| Combustor = Normal | 9 | 285 | 2,685 | 2,409 | 2.52 | 10.3 | 99.9 | 99.9 |
| SD/FF = Normal | 10 | 283 | 1,629 | 2,213 | ND | -35.8 | 100 | 100 |
| With ash recycle |  |  |  |  |  |  |  |  |
| Average |  | 284 | 2,157 | 2,311 | 1.26 | -12.8 | 99.9 | 99.9 |

[a] ND = not detected. Considered as zero in evaluating averages.

Thermal $DeNO_x$ system. These data are presented in "Municipal Waste Combustors - Background Information for Proposed Standards: Control of NO Emissions."[6]

Acid gas data are presented in Table 7-28. Outlet $SO_2$ concentrations ranged from 0.3 to 7.7 ppm at 7 percent $O_2$ over the course of six runs, three at each unit. Outlet $SO_2$ concentations averaged 2.9 ppm at Unit 1 and 5.4 ppm at Unit 2. The lowest $SO_2$ removal efficiency was obtained at the lowest inlet $SO_2$ concentration, but no dependence of $SO_2$ removal efficiency on inlet concentration was observed for the other runs. The corresponding removal efficiencies were above 88 percent for five of six runs with the sixth run at 63.7 percent. The average $SO_2$ removal efficiency was 89.8 percent. The average inlet $SO_2$ levels of 63 ppm are low relative to other MWC's. Outlet HCl concentrations were between 0.6 and 4.1 ppm at 7 percent $O_2$ over six runs. Outlet HCl concentrations averaged 0.7 ppm at Unit 1 and 2.6 ppm at Unit 2. Inlet HCl concentration was not measured. Although outlet $SO_2$ and HCl concentrations were higher at Unit 2, there is no apparent cause for this difference.

The FF inlet temperature was consistent between runs. Although the stoichiometric ratio was not calculated, the effect of lime slurry rate can be evaluated. As shown in Figure 7-9, $SO_2$ removal efficiency increased with increasing lime slurry feed rate for both Units 1 and 2.

Particulate data are presented in Table 7-29. Outlet PM concentrations ranged from 0.0011 to 0.0086 gr/dscf at 12 percent $CO_2$ over the six test runs and averaged 0.0055 gr/dscf for Unit 1 and 0.0022 gr/dscf for Unit 2. Inlet PM was not measured. There was no significant variation in air-to-cloth ratio during testing (3.4 to 3.6 $acfm/ft^2$). Based on these data, the SD/FF at Stanislaus County with a pulse-jet FF operating at $295^oF$ with a net air-to-cloth ratio of 3.6 $acfm/ft^2$ or less, outlet PM emissions of 0.0086 gr/dscf can be achieved.

Metals emission data are presented in Table 7-30. Metals concentrations at the outlet were similar at both units. Arsenic and cadmium concentrations averaged less than 2.5 ug/dscm. Chromium concentrations averaged about 10 ug/dscm, while nickel averaged an outlet concentration of about 20 ug/dscm. The average lead concentrations were

TABLE 7-28. ACID GAS DATA FOR STANISLAUS COUNTY

| Test Condition | Run Number[a] | FF Inlet Temperature (°F) | Lime Slurry Rate (lb/hr) | Acid Gas Concentration (ppmv, dry at 7% $O_2$) | | | $SO_2$ Removal Efficiency (%) |
|---|---|---|---|---|---|---|---|
| | | | | Inlet | Outlet | | |
| | | | | $SO_2$[b] | $SO_2$[b] | HCl | |
| Combustor = Normal | 1-10 | 292 | 303 | 57.6 | 0.3 | 0.88 | 99.5 |
| $DeNO_x$/SD/FF = Normal | 1-11 | 297[c] | 303 | 76.6 | 0.8 | 0.69 | 99.0 |
| | 1-12 | 297[c] | 277 | 66.0 | 7.6 | 0.61 | 88.5 |
| Average (Unit 1) | | 295 | 294 | 66.7 | 2.9 | 0.73 | 95.7 |
| | 2-26 | 291 | 317 | 89.7 | 3.0 | 2.2 | 96.7 |
| | 2-27 | 292 | 292 | 65.5 | 5.6 | 4.1 | 91.5 |
| | 2-28 | 297 | 250 | 21.2 | 7.7 | 1.6 | 63.7 |
| Average (Unit 2) | | 293 | 292 | 58.8 | 5.4 | 2.6 | 84.0 |

[a] Run Number consists of unit number followed by the run number on that unit.

[b] Total sulfur oxides concentration

[c] Temperature monitor at FF inlet malfunctioned. Temperature estimated from measured value at the stack and an assumed temperature drop across the FF (10°F).

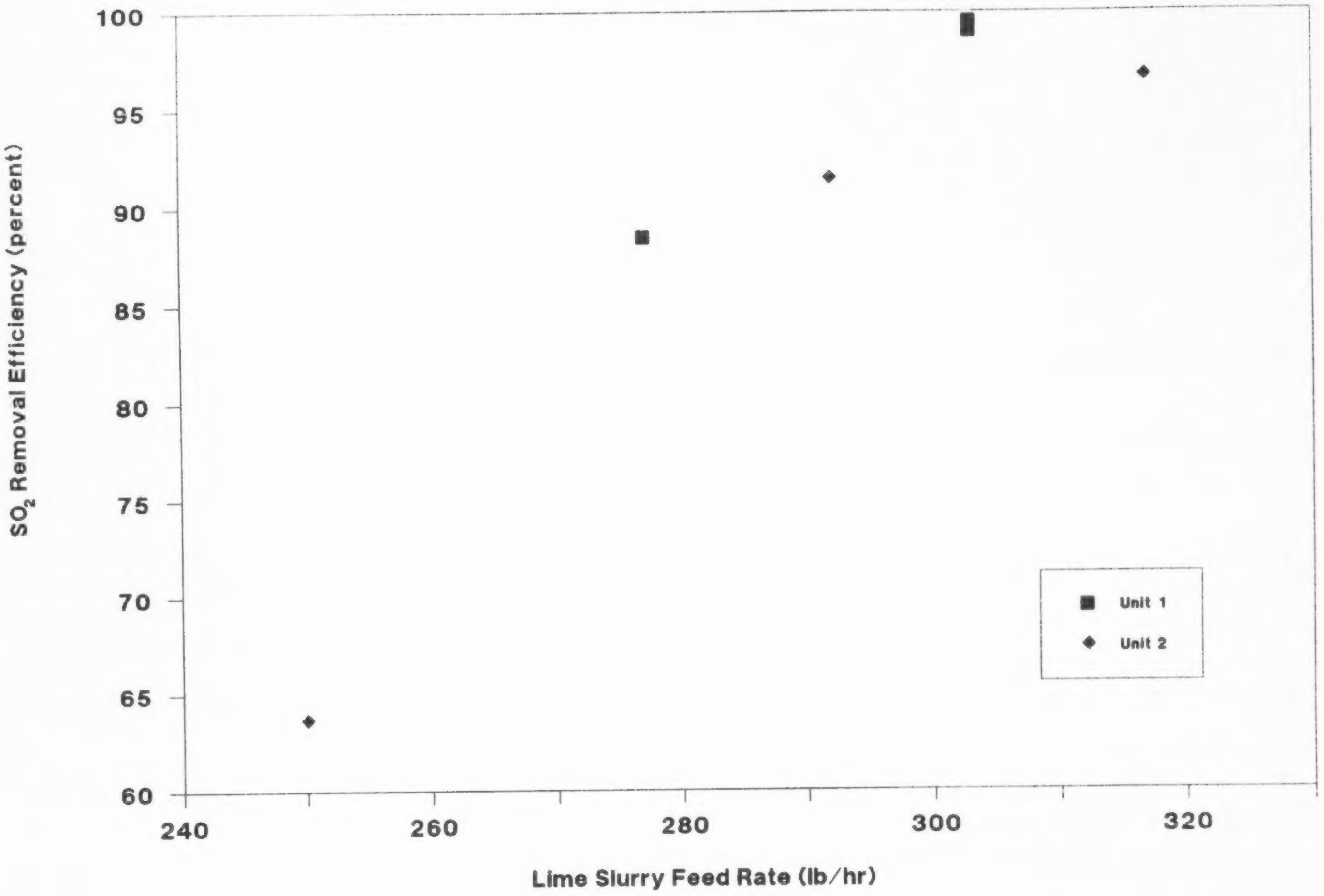


Figure 7-9. $SO_2$ removal efficiency as a function of lime slurry feed rate at Stanislaus County.

TABLE 7-29. PARTICULATE DATA FOR STANISLAUS COUNTY

| Test Condition | Run Number[a] | FF Inlet Temperature (°F) | Flue Gas Flow (acfm) | Outlet PM Concentration (gr/dscf at 12% $CO_2$) |
|---|---|---|---|---|
| Combustor = Normal | 1-10 | 292 | 101,800 | 0.0045 |
| $DeNO_x$/SD/FF = Normal | 1-11 | 297[b] | 100,500 | 0.0034 |
| | 1-12 | 297[b] | 105,000 | 0.0086 |
| Average (Unit 1) | | 295 | 102,400 | 0.0055 |
| | 2-26 | 291 | 103,400 | 0.0027 |
| | 2-27 | 292 | 106,100 | 0.0011 |
| | 2-28 | 297 | 103,300 | 0.0028 |
| Average (Unit 2) | | 293 | 104,300 | 0.0022 |

---

[a] Run Number consists of unit number followed by the run number on that unit.

[b] Temperature monitor at FF inlet malfunctioned. Temperature estimated from measured value at the stack and an assumed temperature drop across the FF (10°F).

## TABLE 7-30. METALS DATA FOR STANISLAUS COUNTY

| Test Condition | Run Number[a] | FF Inlet Temperature (°F) | Outlet PM Concentration[b] (gr/dscf at 12% $CO_2$) | Outlet Concentration (ug/dscm at 7% $O_2$) As | Cd | Cr | Pb | Hg | Ni |
|---|---|---|---|---|---|---|---|---|---|
| Combustor = Normal $\text{DeNO}_x$/SD/FF = Normal | 1-14 | 297[c] | -- | 0.99 | 3.61 | 10.7 | 40.3 | 360 | 30.6 |
|  | 1-16 | 291 | -- | 2.14 | 1.31 | 7.7 | 8.4 | 681 | 15.8 |
|  | 1-19 | 296 | -- | 1.65 | 0.23 | 18.1 | 19.6 | 457 | 31.0 |
| Average (Unit 1) |  | 295 | 0.0055 | 1.59 | 1.72 | 12.2 | 22.8 | 499 | 25.8 |
|  | 2-38 | 297 | -- | 2.24 | 2.07 | 16.6 | 43.0 | 391 | 18.9 |
|  | 2-40 | 287 | -- | ND[d] | 2.49 | 10.5 | 36.3 | 446 | 18.8 |
|  | 2-42 | 287 | -- | ND | 1.76 | 2.3 | 31.0 | 550 | 21.2 |
| Average (Unit 2) |  | 290 | 0.0022 | 0.75 | 2.11 | 9.8 | 36.8 | 462 | 19.6 |
| Overall Average |  | 293 | 0.0038 | 1.17 | 1.91 | 11.0 | 29.8 | 481 | 22.7 |

[a] Run Number consists of unit number followed by the run number on that unit.

[b] PM and metals data not collected simultaneously. Average PM only reported.

[c] Temperature monitor at FF inlet malfunctioned. Temperature estimated from measured value at the stack and an assumed temperature drop across the FF (10°F).

[d] ND = not detected. Considered as zero in evaluating averages.

23 and 37 ug/dscm. Based on typical uncontrolled metals concentrations, these metals were removed at greater than 98 percent. Outlet mercury emissions of 462 and 499 ug/dscm at 7 percent $O_2$, for Unit 2 and Unit 1, respectively, were similar to typical uncontrolled values of 248 to 1,030 ug/dscm (see Section 1.2), suggesting little or no mercury removal.

In Table 7-31, CDD/CDF data are presented. Outlet CDD/CDF concentrations ranged from 4.60 to 8.90 ng/dscm at 7 percent $O_2$ for both units and averaged 6.25 ng/dscm for Unit 1 and 6.53 ng/dscm for Unit 2. Inlet CDD/CDF concentrations were not measured. Thus, the SD/FF at Stanislaus County demonstrated achievable outlet CDD/CDF levels less than 10 ng/dscm.

## 7.3 SUMMARY OF PERFORMANCE

Performance of individual SD/FF systems was evaluated in Section 7.2. The data are evaluated as a whole in this section. Section 7.3.1 evaluates acid gas performance, Section 7.3.2 evaluates particulate performance, Section 7.3.3 evaluates metals performance, and Section 7.3.4 evaluates CDD/CDF performance.

### 7.3.1 Acid Gas

Factors affecting acid gas removal by SD/FF systems include stoichiometric ratio, SD outlet temperature (FF inlet), and inlet $SO_2$ concentration. Increasing stoichiometric ratio increased both $SO_2$ and HCl removal efficiency, as shown in Figures 7-10 and 7-11, respectively. Based on the available data, a stoichiometric ratio in excess of 3 is generally necessary to obtain consistently high acid gas removal efficiencies of 90 percent $SO_2$ and 97 percent HCl.

Also important is the temperature at the SD outlet. Increasing the temperature decreases $SO_2$ and HCl removal efficiencies and prevents SD/FF systems from achieving consistently good performance as shown in Figures 7-12 and 7-13, respectively. Other factors, such as inlet $SO_2$ concentrations, stoichiometric ratio, and type of SD control loop also affect performance.

Better than 90 percent $SO_2$ removal efficiency was demonstrated for at least one run at four of the six facilities with removal efficiency data. One of the two facilities not achieving 90 percent $SO_2$ removal efficiency

TABLE 7-31. CDD/CDF DATA FOR STANISLAUS COUNTY

| Test Condition | Run Number[a] | FF Inlet Temperature (°F) | Outlet CDD/CDF Concentration (ng/dscm at 7% $O_2$) |
|---|---|---|---|
| Combustor = Normal | 1-18 | 305 | 4.60 |
| $DeNO_x$/SD/FF = Normal | 1-21 | 286 | 5.26 |
| | 1-22 | 287 | 8.90 |
| Average (Unit 1) | | 293 | 6.25 |
| | 2-37 | 297 | 6.17 |
| | 2-39 | 292 | 8.45 |
| | 2-45 | 292 | 4.98 |
| Average (Unit 2) | | 294 | 6.53 |

[a] Run Number consists of unit number followed by run number.

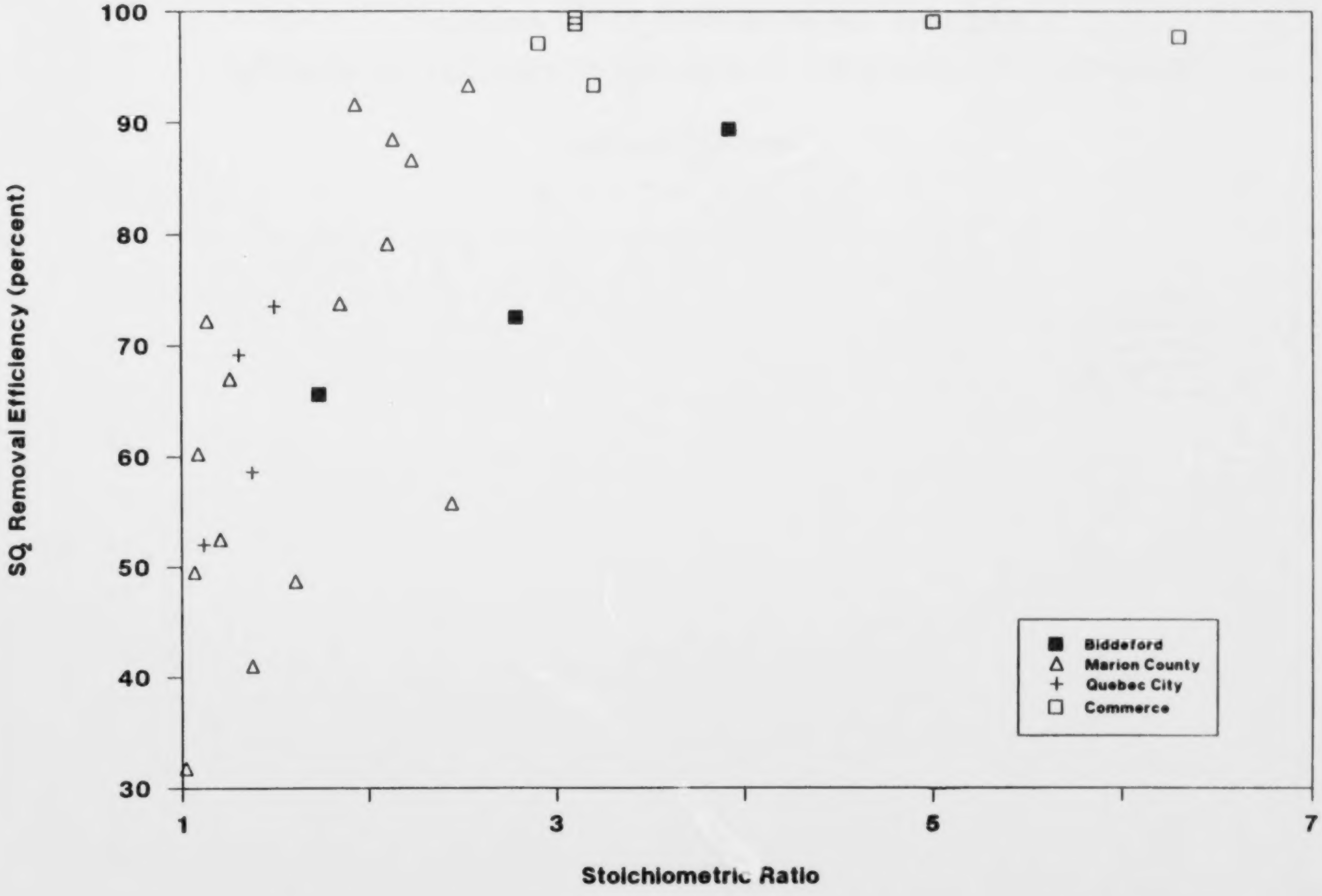


Figure 7-10. $SO_2$ removal efficiency as a function of stoichiometric ratio for SD/FF systems at less than 300°F.

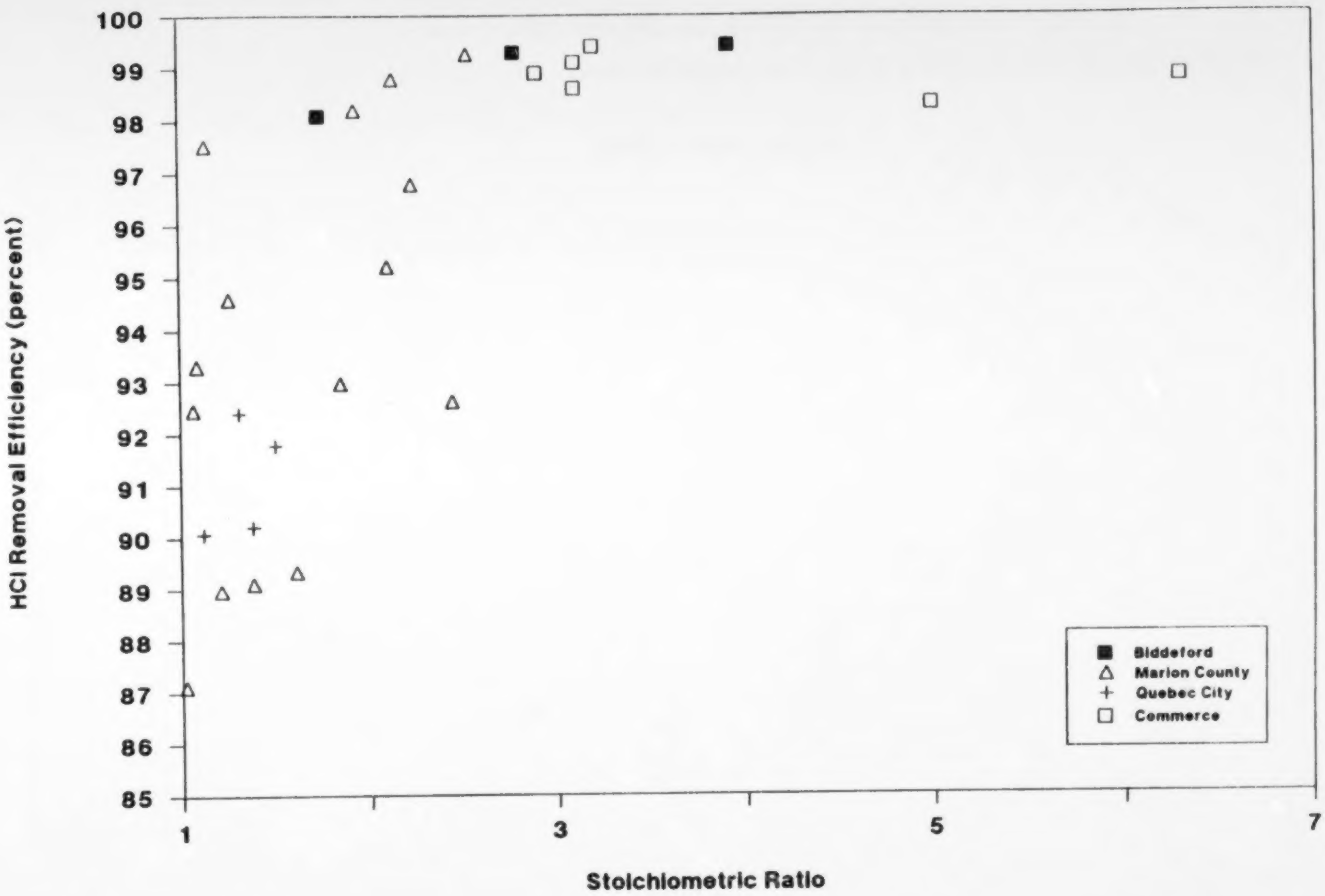


Figure 7-11. HCl removal efficiency as a function of stoichiometric ratio for SD/FF systems at less than 300°F.

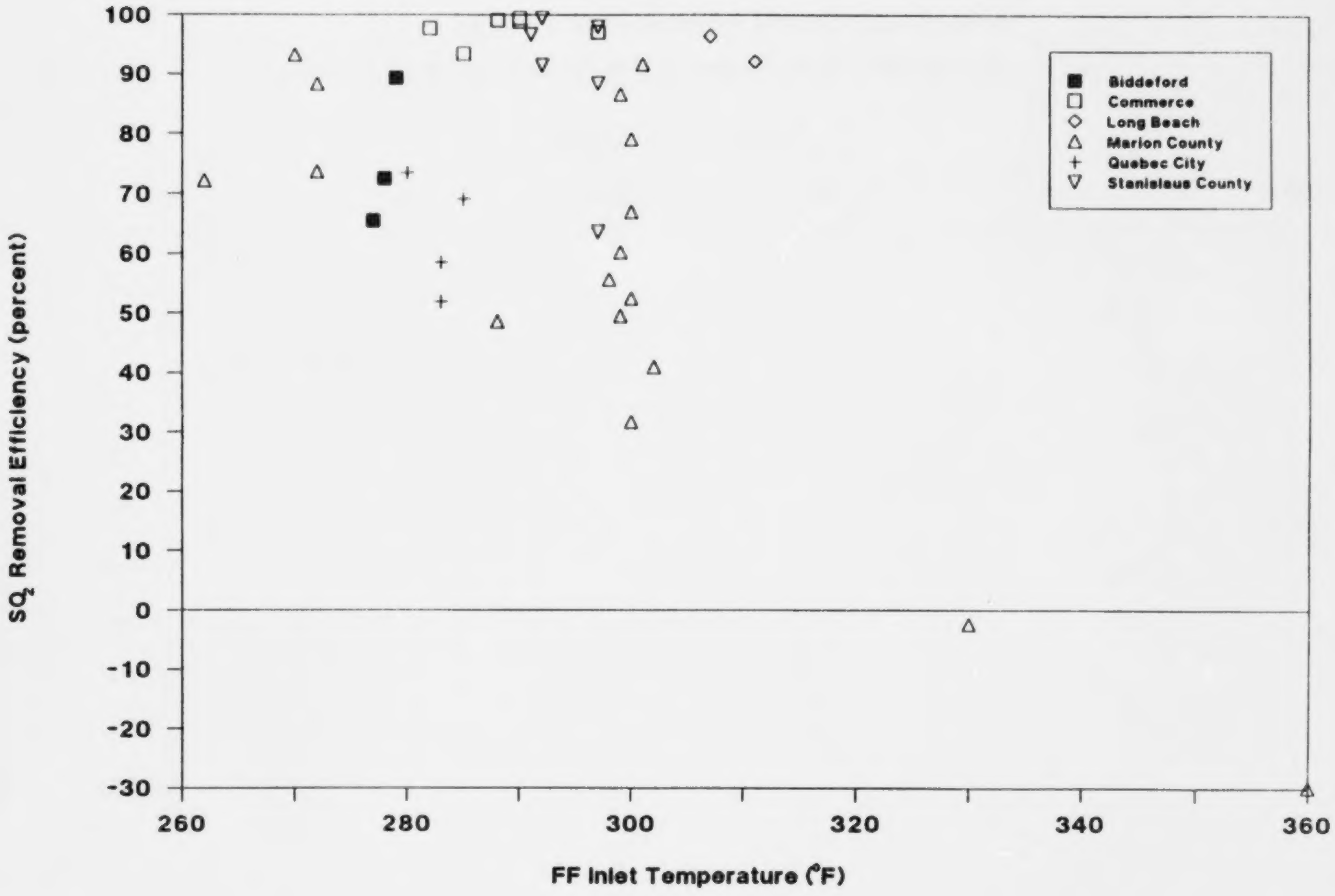


Figure 7-12. $SO_2$ removal efficiency as a function of FF inlet temperature for SD/FF systems.

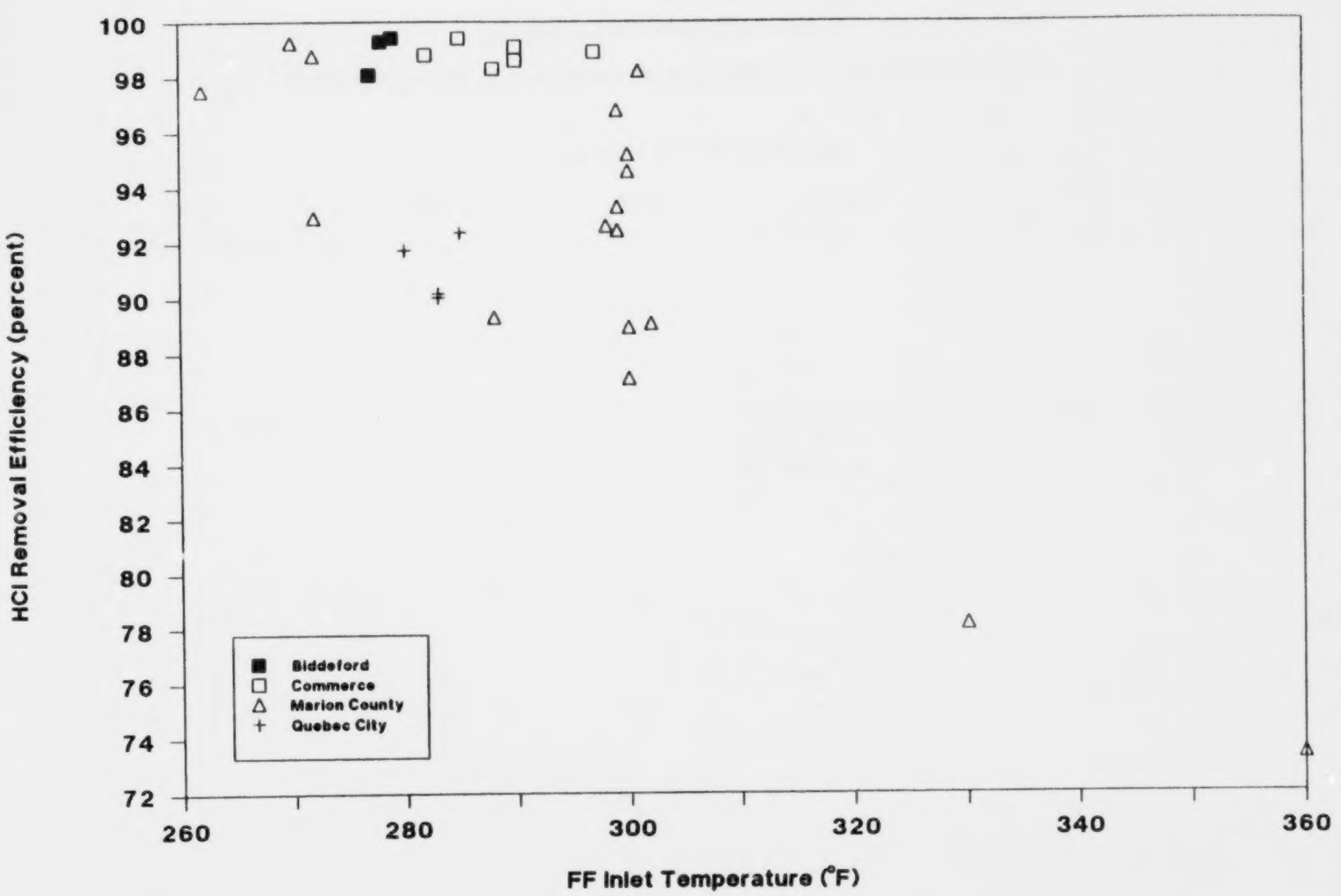


Figure 7-13. HCl removal efficiency as a function of FF inlet temperature for SD/FF systems.

was Biddeford, which had low inlet $SO_2$ concentrations (86 to 129 ppm) and low outlet $SO_2$ concentrations (14 to 31 ppm). At the Quebec City pilot SD/FF, $SO_2$ removal efficiency ranged from 52 to 74 percent. The stoichiometric ratio was consistently less than 1.5 at Quebec City, which probably contributed to the lower $SO_2$ removal efficiencies. Three of the four facilities with HCl removal efficiency data averaged greater than 95 percent HCl removal efficiency. The one facility not demonstrating 95 percent HCl removal efficiency was the Quebec City pilot SD/FF, which operated with a relatively low stoichiometric ratio. In addition, several vendors of SD/FF systems claim that 90 percent $SO_2$ and 95 percent HCl removal efficiencies are readily achievable.[18-20]

### 7.3.2 Particulate Matter

Analysis of PM emissions data from the eight facilities shows that consistently low PM emissions can be obtained. All eight facilities averaged less than 0.01 gr/dscf at 12 percent $CO_2$. These included four reverse-air and four pulse-jet cleaned fabric filters.

### 7.3.3 Metals

Removal efficiencies for arsenic, cadmium, chromium, and lead were consistently demonstrated at 99 percent or greater. Nickel control was variable from site to site. At two sites, nickel removal efficiency was measured at greater than 99 percent. At another two sites, nickel removal was measured at 14 and 50 percent. At two sites where only outlet nickel emissions were measured, removal efficiencies of greater than 98 percent are suggested. There is no apparent reason for the widely varying performance.

Mercury removal varied from site to site. Inlet and outlet mercury concentrations were measured during five separate test programs at four facilities, with the average removal efficiencies of 100, 80.0, 0, 86.3, and 94.8 percent obtained. Zero mercury removal efficiency was obtained during one test program at Commerce. Later tests at Commerce demonstrated an average of 80 percent mercury removal. Three of these runs were conducted firing commercial refuse and averaged 70 percent mercury removal efficiency. The removal of mercury did not appear to depend solely on FF inlet temperature.

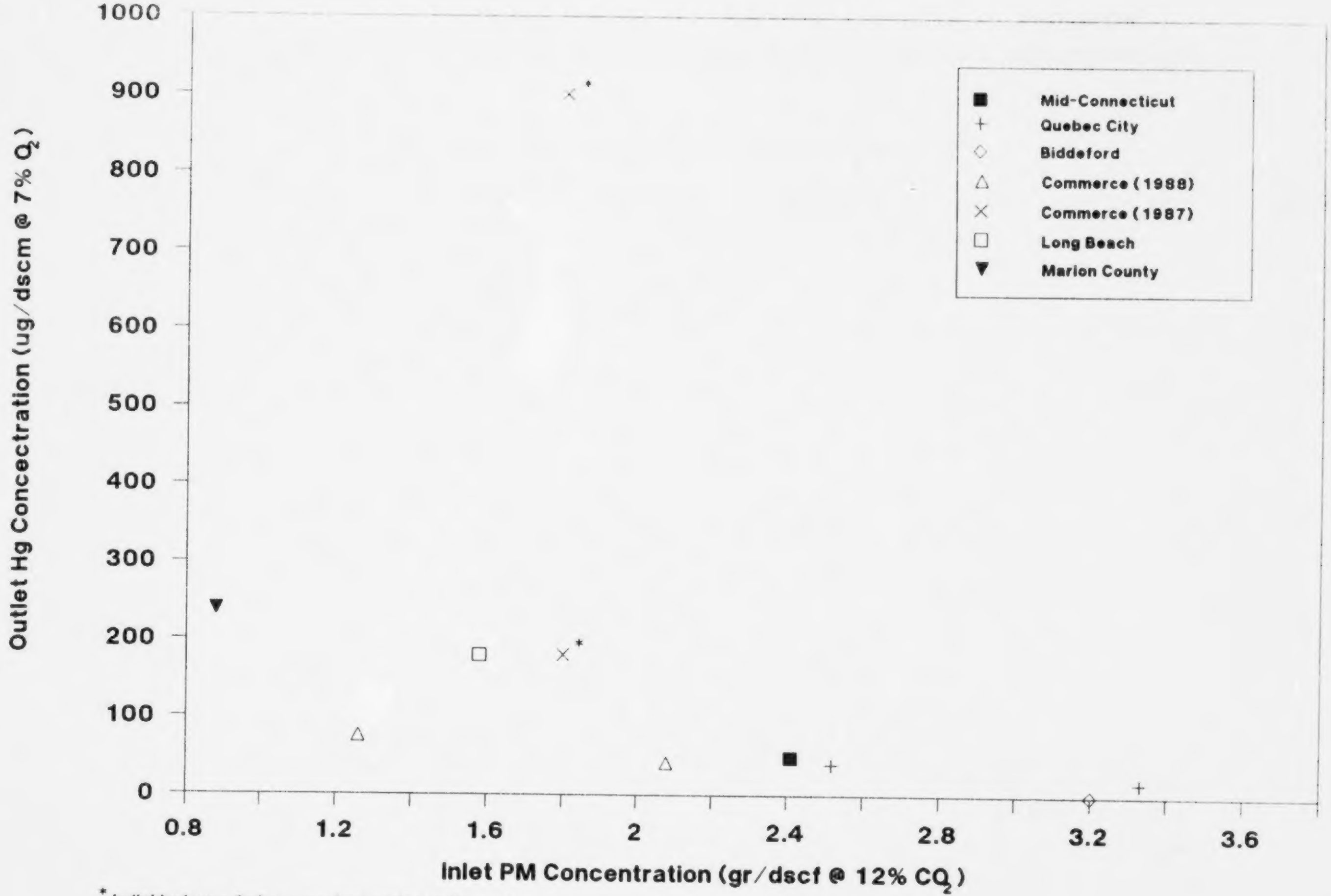
Outlet mercury concentrations at 10 separate test programs ranged from not detected to 940 ug/dscm. The average concentration of all these test programs was 250 ug/dscm. Emissions from seven of the 10 test programs were less than 240 ug/dscm.

It has been theorized that mercury removal is enhanced by carbon in the fly ash providing adsorption sites for the mercury.[21] In Figure 7-14, mercury concentration at the outlet is plotted as a function of inlet PM concentration. These data suggest decreased mercury emissions with increasing inlet PM concentration. In Figure 7-15, mercury emissions are plotted as a function of inlet CDD/CDF concentration. Recognizing that increased CDD/CDF concentrations may be associated with increased carbon in the PM, the graph indicates decreased mercury emissions for higher inlet CDD/CDF concentrations and thus, more carbon in the PM.

Based on measured removal efficiencies of metals by SD/FF systems, arsenic, cadmium, chromium, and lead can be removed at 99 percent efficiency. Nickel removal is generally high (98 percent), but varies. The level of mercury removal by SD/FF systems is uncertain, but an emission level of 300 ug/dscm appears achievable.

### 7.3.4 CDD/CDF

Outlet CDD/CDF concentrations during normal combustor operation were less than 9.8 ng/dscm for all runs. The average outlet CDD/CDF concentrations were below 6.4 ng/dscm for the eight facilities. These results were obtained at inlet CDD/CDF concentrations ranging from 27 to 1,000 ng/dscm and FF inlet temperatures of 270 to 300°F. Thus, spray dryer/fabric filter systems operating at FF inlet temperatures of 300°F or less can consistently achieve average outlet CDD/CDF concentrations of less than 10 ng/dscm at 7 percent $O_2$.



* Individual runs during same test period at Commerce.

Figure 7-14. Effect of inlet PM on mercury emissions for systems with spray dryer/fabric filter systems

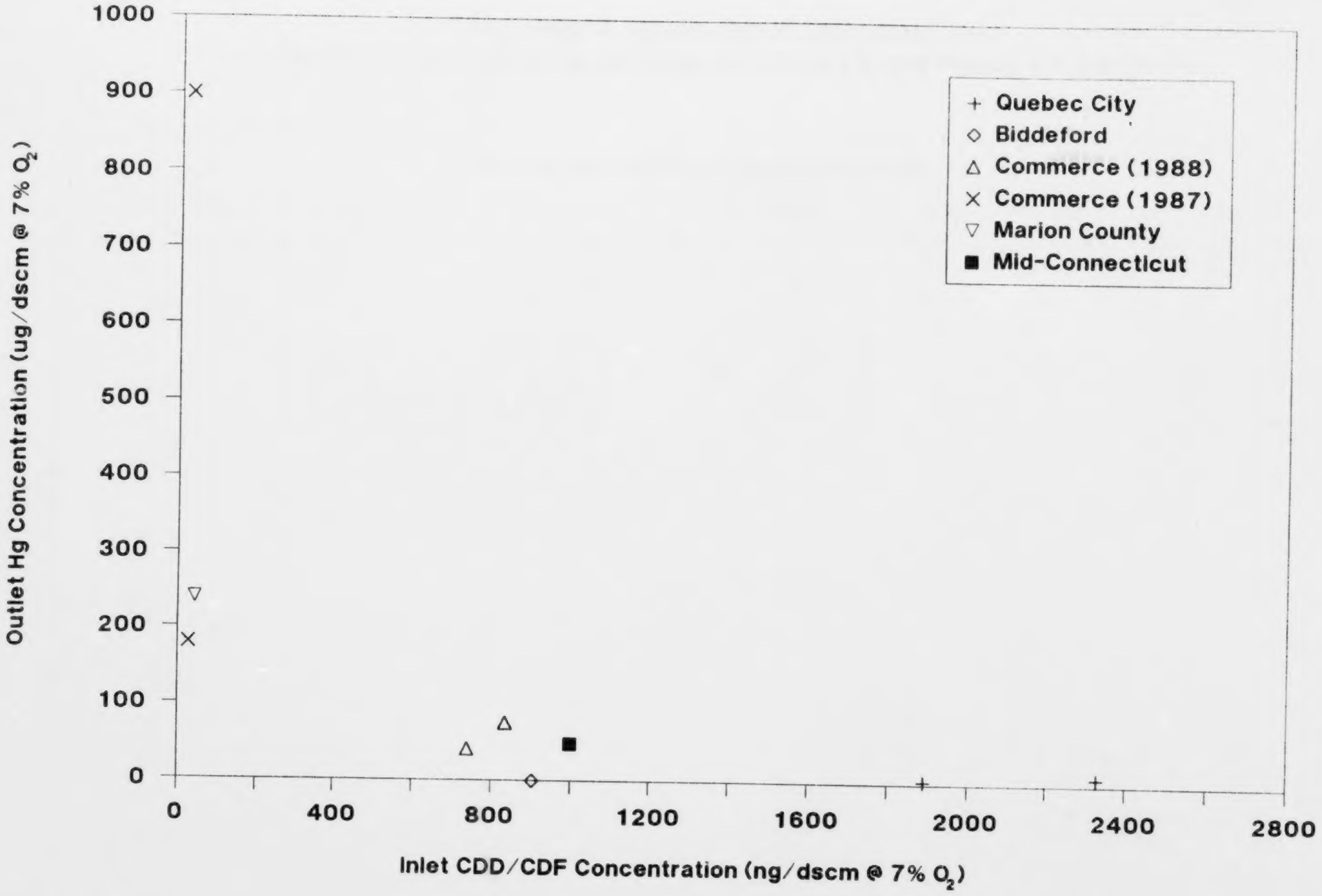


Figure 7-15. Effect of inlet CDD/CDF on mercury emissions for MWCs with spray dryer/fabric filter systems

## 7.4 REFERENCES

1. Klamm, S., G. Scheil, M. Whitacre, J. Surman (Midwest Research Institute), and W. Kelly (Radian Corporation). Emission Testing at an RDF Municipal Waste Combustor. Prepared for U.S. Environmental Protection Agency, North Carolina. EPA Contract No. 68-02-4453, May 6, 1988.

2. Letter with attachments from G. M. Bates, Main Energy Recovery Company (MERC), to J.R. Farmer, U.S. Environmental Protection Agency, ESD. No date. Response to information request.

3. McDannel, M. D., L. A. Green, and B. L. McDonald (Energy Systems Associates). Air Emissions Tests at Commerce Refuse-to-Energy Facility, May 26 - June 5, 1987. Prepared for County Sanitation Districts of Los Angeles County. Whittier, California. July 1987.

4. McDannel, M. D., L. A. Green, and A. C. Bell (Energy Systems Associates). Results of Air Emission Test During the Waste-to-Energy Facility. Prepared for County Sanitation Districts of Los Angeles County, Whittier, California. December 1988.

5. Interview of J. Donnelly, Joy Technologies, Inc. by D. M. White, Radian Corporation. April 13, 1989.

6. Municipal Waste Combustors--Background Information for Proposed Standards: Control of $NO_x$ Emissions. U. S. Environmental Protection Agency. EPA-450/3-89-27d. August 1989.

7. Ethier, D. D., L. N. Hottenstein, and E. A. Pearson (TRC Environmental Consultants). Air Emission Test Results at the Southeast Resource Recovery Facility Unit 1, October - December, 1988. Prepared for Dravo Corporation, Long Beach, California. February 28, 1989.

8. Anderson, C. L. (Radian Corporation). CDD/CDF, Metals, and Particulate Emissions Summary Report, Mid-Connecticut Resource Recovery Facility, Hartford, Connecticut. Prepared for U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. EMB Report No. 88-MIN-09A. January 1989.

9. Vancil, M. A. and C. L. Anderson (Radian Corporation). Summary Report, CDD/CDF, Metals, HCl, $SO_2$, $NO_x$, CO and Particulate Testing, Marion County Solid Waste-to-Energy Facility, Inc., Ogden Martin Systems of Marion, Brooks, Oregon. Prepared for U.S. Environmental Protection Agency. EMB Report No. 86-MIN-03A. September 1988.

10. Letter Report from M. A. Vancil, Radian Corporation to C. E. Riley, EMB Task Manager, U.S. Environmental Protection Agency. Emission Test Results for the PCDD/PCDF Internal Standards Recovery Study Field Test: Runs 1, 2, 3, 5, 13, 14. July 24, 1987.

11. Anderson, C. L., K. L. Wertz, M. A. Vancil, and J. W. Mayhew (Radian Corporation). Shutdown/Startup Test Program Emission Test Report, Marion County Solid Waste-to-Energy Facility, Inc., Ogden Martin Systems of Marion, Brooks, Oregon. Prepared for U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. EMB Report No. 87-MIN-4A. September 1988.

12. Anderson, C. L., et. al. (Radian Corporation. Characterization Test Report, Marion County Solid Waste-to-Energy Facility, Inc., Ogden Martin Systems of Marion, Brooks, Oregon. Prepared for U. S. Environmental Protection Agency, Research Triangle Park, North Carolina. EMB Report No. 86-MIN-04. September 1988.

13. Roy F. Weston, Incorporated. Penobscot Energy Recovery Company Facility, Orrington, Maine, Source Emissions Compliance Test Report Incinerator Units A and B (Penobscot, Maine). Prepared for GE Company. September 1988.

14. Zaitlin, S., State of Maine, Department of Environmental Protection, Board of Environmental Protection. Air Emission License Finding of Fact and Order, Penobscot Energy Recovery Company, Orrington, Maine. February 26, 1986.

15. The National Incinerator Testing and Evaluation Program: Air Pollution Control Technology. EPS 3/UP/2, Environment Canada, Ottawa, September 1986.

16. Hahn, J. L. (Ogden Projects, Inc.) Environmental Test Report. Prepared for Stanislaus Waste Energy Company, Crows Landing, California. OPI Report No. 177R. April 7, 1989.

17. Hahn, J. L. and D. S. Sofaer. Air Emissions Test Results from the Stanislaus County, California Resource Recovery Facility. Presented at the International Conference on Municipal Waste Combustion. Hollywood, Florida. April 11-14, 1989. pp. 4A-1 to 4A-14.

18. Telecon. D. M. White, Radian Corporation, with J. Donnelly, Joy, Inc. June 12, 1989. Achievable acid gas reductions and retrofit times.

19. Telecon. D. M. White, Radian Corporation, with J. Buschmann, Flakt, Inc. June 8, 1989. Achievable acid gas reductions and retrofit times.

20. Telecon. D. M. White, Radian Corporation, with J. Zmuda, Research-Cottrell, Inc. June 8, 1989. Achievable acid gas reductions and retrofit times.

21. Personal communication. Hahn, J., Odgen Projects, Inc. and M. Johnston, EPA/OAQPS. April 1989.

# APPENDIX A. HYDROGEN CHLORIDE AND SULFUR DIOXIDE EMISSIONS DATA

## A.1 INTRODUCTION

This appendix reviews emission data from two MWC's equipped with spray dryers to (1) investigate relationships between HCl and $SO_2$ removal behavior and (2) assess the variability of $SO_2$ emissions. The two MWC's evaluated are the Millbury Resource Recovery Facility in Millbury, Massachusetts and the Marion County Solid Waste-to-Energy Facility in Brooks, Oregon. A brief description for each facility is provided in Section A.2. Section A.3 describes the data collected at each facility. Section A.4 examines the relationship between HCl and $SO_2$ emissions and removal efficiency for these two data sets. Section A.5 examines the variability in $SO_2$ emissions at the Millbury MWC.

## A.2 FACILITY DESCRIPTIONS

### A.2.1 Millbury[1]

The Millbury facility consists of two identical furnace, boiler, and flue gas treatment systems. Each furnace is designed to process 750 tons/day of MSW. Acid gas and particulate emissions from each furnace are controlled by separate spray dryer and electrostatic precipitator (ESP) systems. The Millbury facility was designed, constructed, and is operated by Wheelabrator Environmental Systems, Inc. HCl and $SO_2$ data were collected from Unit 2 as part of a two-month test program conducted during July - September, 1988.

A process schematic for Unit 2 is shown in Figure A-1. MSW is charged to a Babcock and Wilcox waterwall furnace and boiler unit that is equipped with a Von Roll reciprocating, inclined grate. Each boiler is rated to produce about 190,000 lb/hr of superheated steam at $825^{\circ}F$ and 850 psia. The combined steam from the two units is supplied to a turbine/generator set which is rated at 40 megawatts. Auxiliary fuel (natural gas) is used during startup and shutdown and during low load operation. The furnace flue gases pass up through the waterwall section of the furnace and then into superheater and economizer heat transfer passes. After passing through the spray dryer and ESP, the flue gas exhausts to the atmosphere through a reinforced concrete stack which is common to both units.

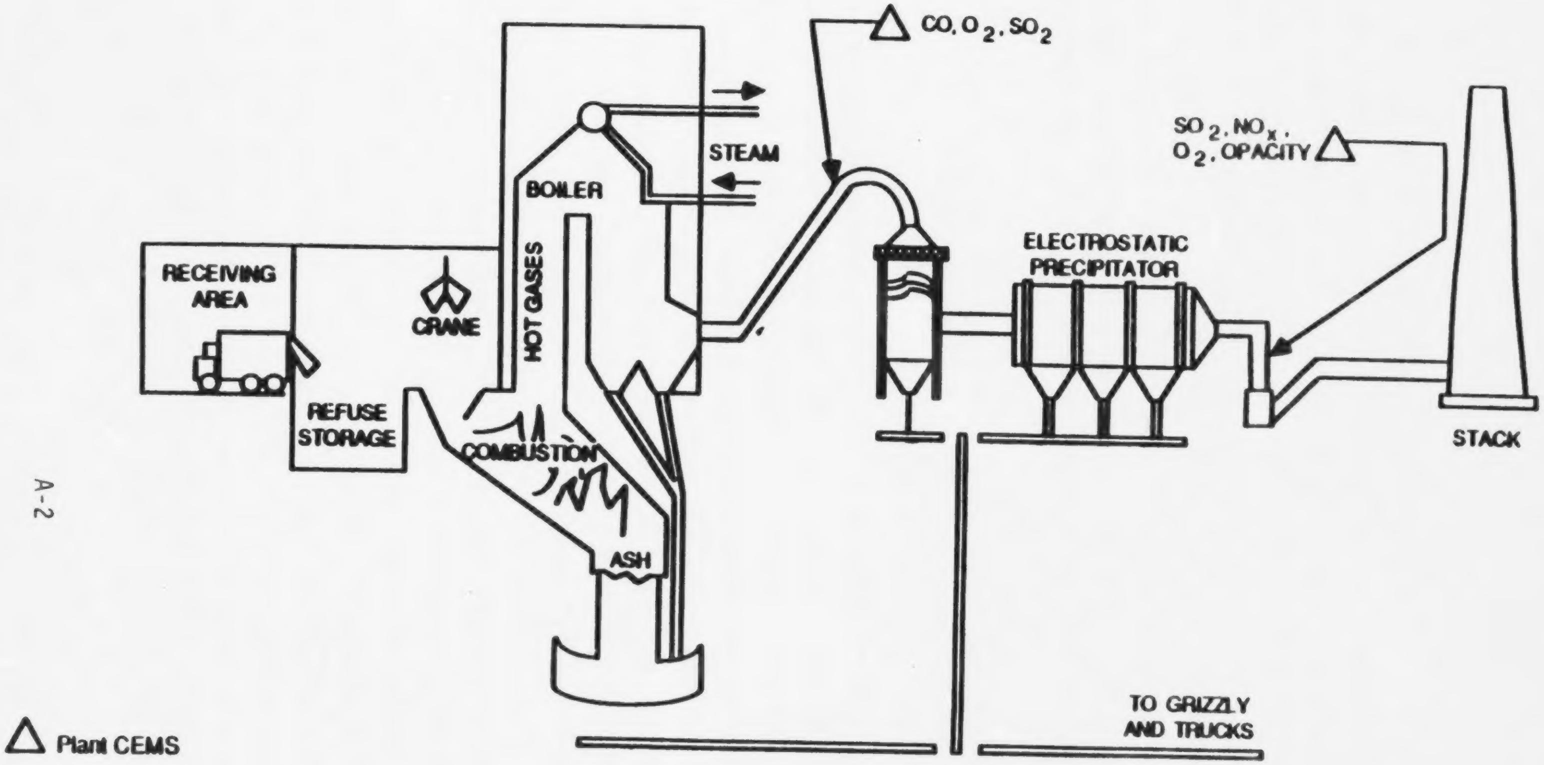

RECEIVING AREA
REFUSE STORAGE
CRANE
HOT GASES
BOILER
STEAM
COMBUSTION
ASH
$CO, O_2, SO_2$
ELECTROSTATIC PRECIPITATOR
$SO_2, NO_x, O_2$, OPACITY
STACK
TO GRIZZLY AND TRUCKS
Plant CEMS

Figure A-1. Millbury Resource Recovery Facility process schematic.

The emissions control system was designed by Wheelabrator Air Pollution Control Systems. Slaked lime, along with metered dilution water, is injected into the dryer vessel through two-fluid nozzles. The lime slurry feed rate is automatically controlled to achieve either an $SO_2$ emission rate (the unit is permitted for a maximum $SO_2$ concentration at the stack of 0.21 lbs per million Btu of MSW fired) or a percent $SO_2$ removal efficiency requirement, whichever is more stringent. Dilution water is added to the lime slurry to reduce the flue gas temperature. The spray dryer outlet temperature is typically controlled around $255^{o}F$. The dry solids and fly ash from the spray dryer are collected in a three-field ESP having a design SCA of 333 $ft^2$ per 1,000 acfm at a flue gas flow rate of 160,000 acfm.

During the emission test program, $SO_2$, HCl, oxygen ($O_2$), and other flue gas constituents were measured between the furnace and the spray dryer (inlet conditions) and between the ESP and fan (outlet conditions). A discussion of the continuous emission monitors employed and other relevant information about the test program is contained in the test report.[1]

### A.2.2 Marion County[2]

The Marion County MWC consists of two identical 275-ton/day, mass burn, waterwall Martin GmbH combustors followed by Teller-designed air pollution control systems. Figure A-2 presents a process diagram for one of the two trains. The Marion County MWC was designed, constructed, and operated by Ogden-Martin, Inc. Testing was conducted on Unit No. 1 in June 1987 to characterize the performance of the air pollution control system.

The air pollution control system consists of a cyclone, spray dryer, a dry venturi, and a fabric filter. The flue gases leave the economizer section and enter the bottom of the quench reactor through a cyclone where oversize particles are removed. Slaked pebble lime slurry is injected through an array of five two-fluid nozzles near the bottom of the reactor vessel. The feed rate is varied to maintain the quench reactor outlet temperature within an operating range of $125\text{-}149^{o}C$ ($258\text{-}300^{o}F$). The stoichiometric ratio of lime to HCl is maintained at approximately 2 - 2.5 to ensure that peaks in acid gas levels are sufficiently controlled. The system design did not allow the lime feed rate to be changed independently

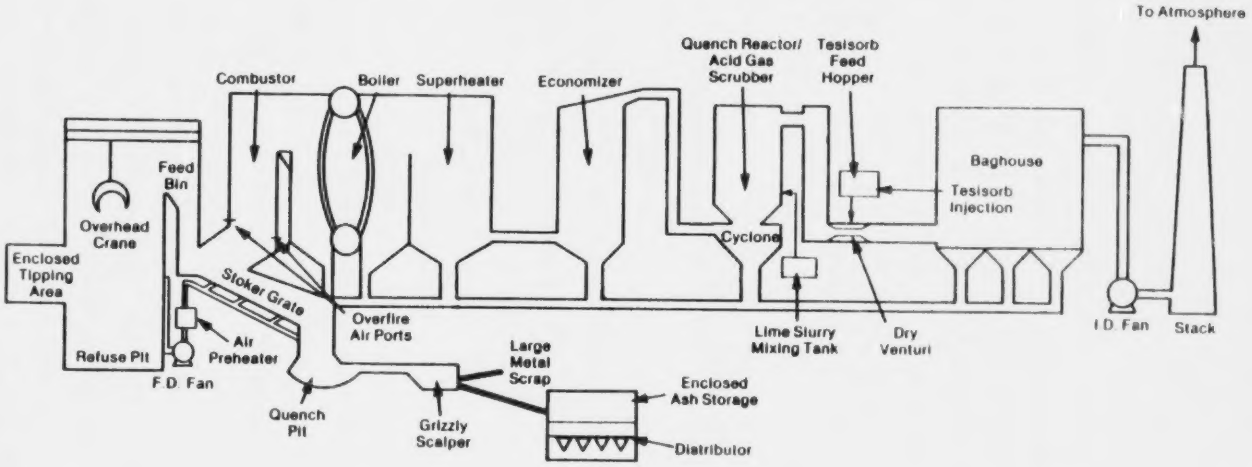

To Atmosphere
Combustor
Boiler
Superheater
Economizer
Quench Reactor/ Acid Gas Scrubber
Tesisorb Feed Hopper
Baghouse
Tesisorb Injection
Feed Bin
Overhead Crane
Enclosed Tipping Area
Refuse Pit
Stoker Grate
Air Preheater
F.D. Fan
Overfire Air Ports
Cyclone
Lime Slurry Mixing Tank
Dry Venturi
I.D. Fan
Stack
Large Metal Scrap
Enclosed Ash Storage
Distributor
Quench Pit
Grizzly Scalper

Figure A-2. Marion County Solid Waste-to-Energy Facility process schematic.

of the water feed rate. The lime concentration in the slurry is held nearly constant. Therefore, as the water feed rate increases so did the lime flow.

A low pressure drop dry venturi located between the spray dryer and the baghouse was used to inject Tesisorb, a proprietary sorbent, into the flue gas at a set rate.

An Amerthem reverse air baghouse is located downstream of the dry venturi for particulate collection. Each baghouse consists of six compartments with 120 bags in each. The design air-to-cloth ratio is 2.3 acfm/$ft^2$ at a flue gas flow rate of 60,000 acfm. Particulate, lime, and Tesisorb cake collected on the fabric is removed every 60 to 70 minutes. Unspent lime in the filter cake provides an additional opportunity for acid gas collection.

During the June 1987 test program, HCl, $SO_2$, $O_2$, and other parameters were measured between the economizer and the cyclone (inlet to control devices) and at the breeching to the outlet stack (control devices outlet). Gas measurements were also collected between the spray dryer and baghouse, but were not used in the present analysis. More information about the continuous emission monitors, testing procedures, and other related aspects of plant operation is contained in the test report.[2]

## A.3 DATA BASE DESCRIPTION

### A.3.1 Millbury Data Base.

At the Millbury MWC, emission monitoring and process data were collected on an hourly basis over 62 days during July and August, 1988. During this period, the combustor and air pollution control systems were operated "normally" by plant personnel.

The CEM data used in this analysis include hourly average $O_2$, HCl, and $SO_2$ measurements collected at both the inlet and outlet of the spray dryer/ESP system. The HCl and $SO_2$ gas concentrations were adjusted to 7 percent $O_2$ using the applicable $O_2$ measurements. Outlet HCl measurements collected via CEM were compared to those collected by wet chemistry reference methods on several occassions during the testing to determine the accuracy of CEM measurements. These comparisons showed significant scatter in the data at CEM measurements below 4 ppm and reference method (RM) measurements below

10 ppm. Since the reliability of these low measurements is questionable, it was decided for this analysis to adjust all HCl CEM measurements below 4 ppm to a value of 10 ppm. This procedure results in a conservatively high estimate of outlet HCl emissions. However, because outlet HCl concentrations of 10 ppm typically correspond to HCl removal efficiencies of roughly 98 percent, this conservatism in estimating outlet HCl emissions is not expected to materially influence the analysis of HCl removal effeciencies.

For HCl CEM measurements above 4 ppm, the following correlation was developed based comparison of RM and CEM measurements:

$$HCL_{RM} = 2.33\ HCl_{CEM} + 2.1.$$

This correlation (valid up to RM measurements up to 40 ppm) was employed in the analysis to adjust outlet HCl CEM measurements above 4 ppm HCl.

No adjustments were made to inlet HCl CEM measurements or to inlet/outlet $SO_2$ measurements (other than $O_2$ basis adjustments) due to acceptable agreement between CEM and RM measurements.

### A.3.2 Marion County Data Base.

Emission data for the Marion County MWC were collected during the "combustor variation" phase of the facility characterization test program. During this testing phase, combustion operating parameters were intentionally varied to demonstrate their impacts on temperature profile, combustion efficiency, and other parameters of interest. The spray dryer/fabric filter system, however, was maintained at normal operating conditions. Thus, the HCl and $SO_2$ data reflect a wide range on spray dryer inlet gas conditions. During each test condition, emissions data were collected over a two or three hour period. A summary of the test conditions and combustion operating characteristics is provided in Table A-1.

The CEM data used in this analysis include hourly average $O_2$, HCl, and $SO_2$ measurements collected at both the inlet and outlet of the spray dryer/fabric filter system. Three hourly average measurements were available for each test run with the exception of Runs 3A, 6B, and 8, for which only two hourly average measurements were available.

TABLE A-1. SUMMARY OF TEST CONDITION PARAMETERS FOR MARION COUNTY COMBUSTOR VARIATION TESTS

| Test Run No. | Combustor Condition |
|---|---|
| 1 | Baseline (i.e., normal operation) |
| 2 | Baseline (i.e., normal operation) |
| 3A | Low load; low excess air |
| 3B | High excess air |
| 4 | Low overfire air |
| 5 | High overfire air |
| 6A | Low load |
| 6B | Low load; high excess air |
| 7 | Low load; low excess air |
| 8 | Low load; low overfire air |
| 9 | Low load; high overfire air |

As with the Millbury data, the HCl and $SO_2$ gas concentrations for Marion County were adjusted to a 7 percent $O_2$ basis using the applicable $O_2$ measurements. No other adjustments were made to the data.

## A.4 RELATIONSHIP BETWEEN HCl AND $SO_2$ EMISSIONS

This section examines the relationship between controlled HCl and SO2 emissions for MWC's equipped with spray dryers. Two measures of emissions control are examined using the Millbury and Marion County MWC data: outlet emission levels and pollutant removal efficiency.

### A.4.1 HCl Removal Efficiency Versus $SO_2$ Removal Efficiency

Since both HCl and $SO_2$ are acid gases, they are expected to be absorbed by the alkaline lime slurry used in spray dryers. Theoretically, the reaction of a strong acid gas such as HCl with dissolved calcium proceeds rapidly. The reaction of $SO_2$ proceeds more slowly and over a narrower pH range. Moreover, the rate of HCl absorption is faster than that for $SO_2$.[3] As a result, HCl is expected to be preferentially absorbed relative to $SO_2$, resulting in higher HCl removal efficiencies than $SO_2$ removal efficiencies.

Pollutant removal efficiency is defined as:

$$\frac{C_{in} - C_{out}}{C_{in}} \times 100 = \% \text{ Removal Efficiency}$$

where $C_{in}$ is the measured concentration of HCl or $SO_2$ at the spray dryer system inlet and $C_{out}$ is the measured concentration at the particulate matter control device outlet. All pollutant concentrations are adjusted to 7 percent $O_2$.

Millbury Results. At the Millbury facility, inlet HCl concentrations averaged 770 ppm while inlet $SO_2$ concentrations averaged approximately 200 ppm. A plot comparing HCl removal efficiency with $SO_2$ removal efficiency for the Millbury data is shown in Figure A-3. Each data point represents a 24-hour average. The data show a general positive correlation between HCl and $SO_2$ removal--that is, the highest HCl removal efficiencies are associated with the highest $SO_2$ removal efficiencies; the lowest HCl removal efficiencies are associated with the lowest $SO_2$ removal efficiencies. The HCl removal efficiency was above 95 percent in all cases and generally was between 98 and 99 percent. In contrast, the $SO_2$ removal efficiency was

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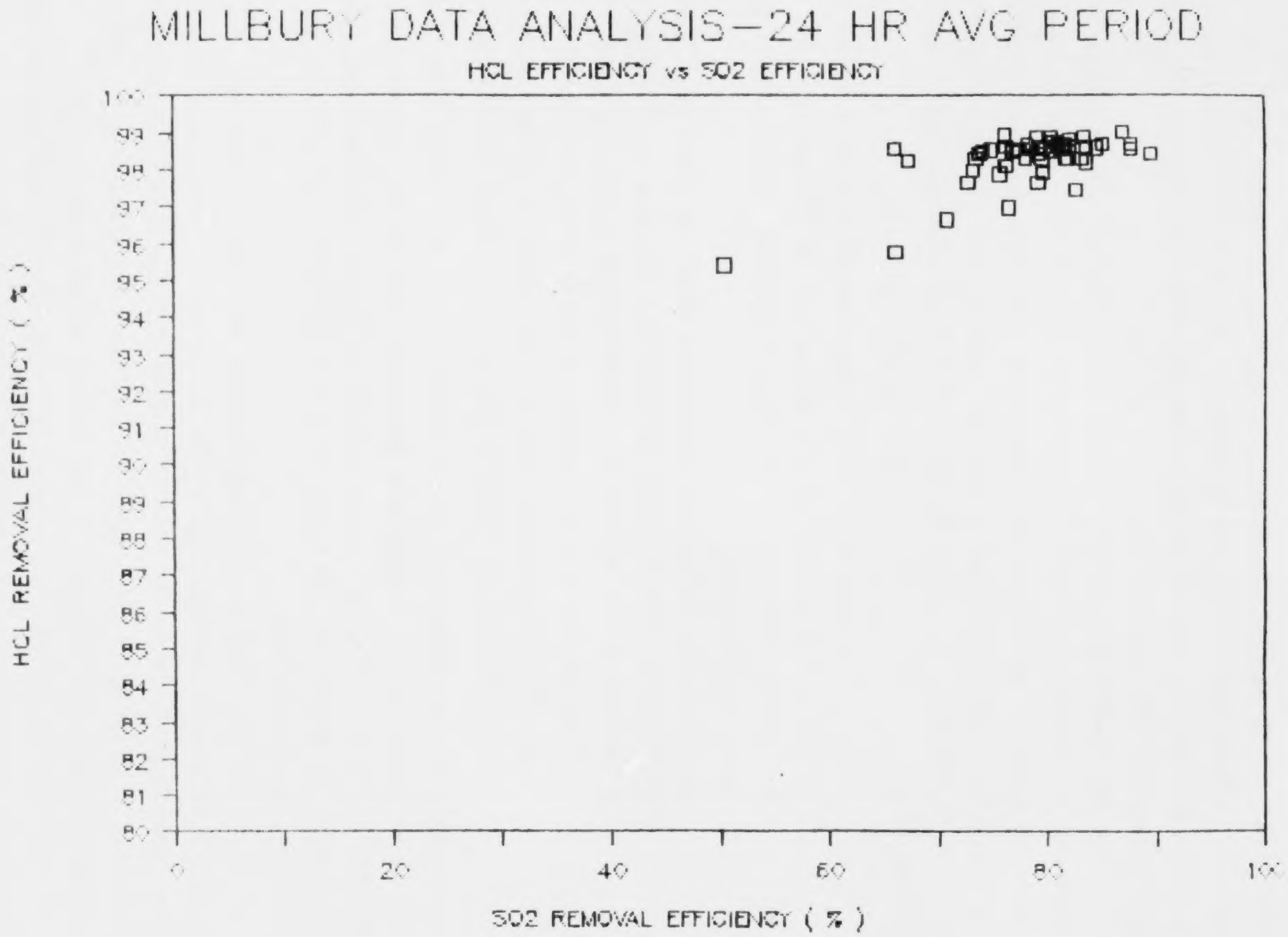

Figure A-3. HCl removal efficiency vs. $SO_2$ removal efficiency at Millbury (24-hour averages).

always lower, generally between 70 and 90 percent. The lowest $SO_2$ removal efficiency of 50 percent was associated with an HCl removal efficiency of 95 percent. These results clearly demonstrate a predictable relationship between HCl and $SO_2$ removal efficiencies and show that removal efficiencies are higher for HCl than for $SO_2$.

The two lowest HCl and $SO_2$ removal efficiency values in Figure A-3 were examined as possible outliers. A review of process data from the two days in question (July 21 and August 15) showed that both days were characterized by unusually high spray dryer outlet gas temperatures during a significant portion of the day. A review of the control room operator log showed the following:

- On July 21, spray dryer outlet gas temperatures were intentionally set at a higher level to dry out an ash/solids hopper. The hopper had become moist due to blockage of atomizer air in one of the spray dryer nozzles.
- On August 15, no obvious reason was found for the higher spray dryer outlet temperatures although the increase occurred just after a failure of the automatic control system on No. 1 boiler. The high outlet temperatures persisted after automatic control was re-established, however, and did not return to normal levels until the boiler load was reduced approximately eight hours later.

Spray dryer outlet temperature is an important variable which affects HCl and $SO_2$ absorption. As the temperature increases, HCl and $SO_2$ absorption generally decline. However, since neither of these operating events was considered to be outside the range of normal operating variability, no data were excluded as outliers.

A plot of HCl removal efficiency versus $SO_2$ removal efficiency was also examined for 8-hour averages, as shown in Figure A-4. This plot shows the same general findings as the plot of 24-hour averages, although the data are more scattered owing to the higher variability associated with shorter averaging times (see Section A.5 for further discussion).

The positive correlation between HCl removal efficiency and $SO_2$ removal efficiency is noteworthy. Since both HCl and $SO_2$ gases are competing for

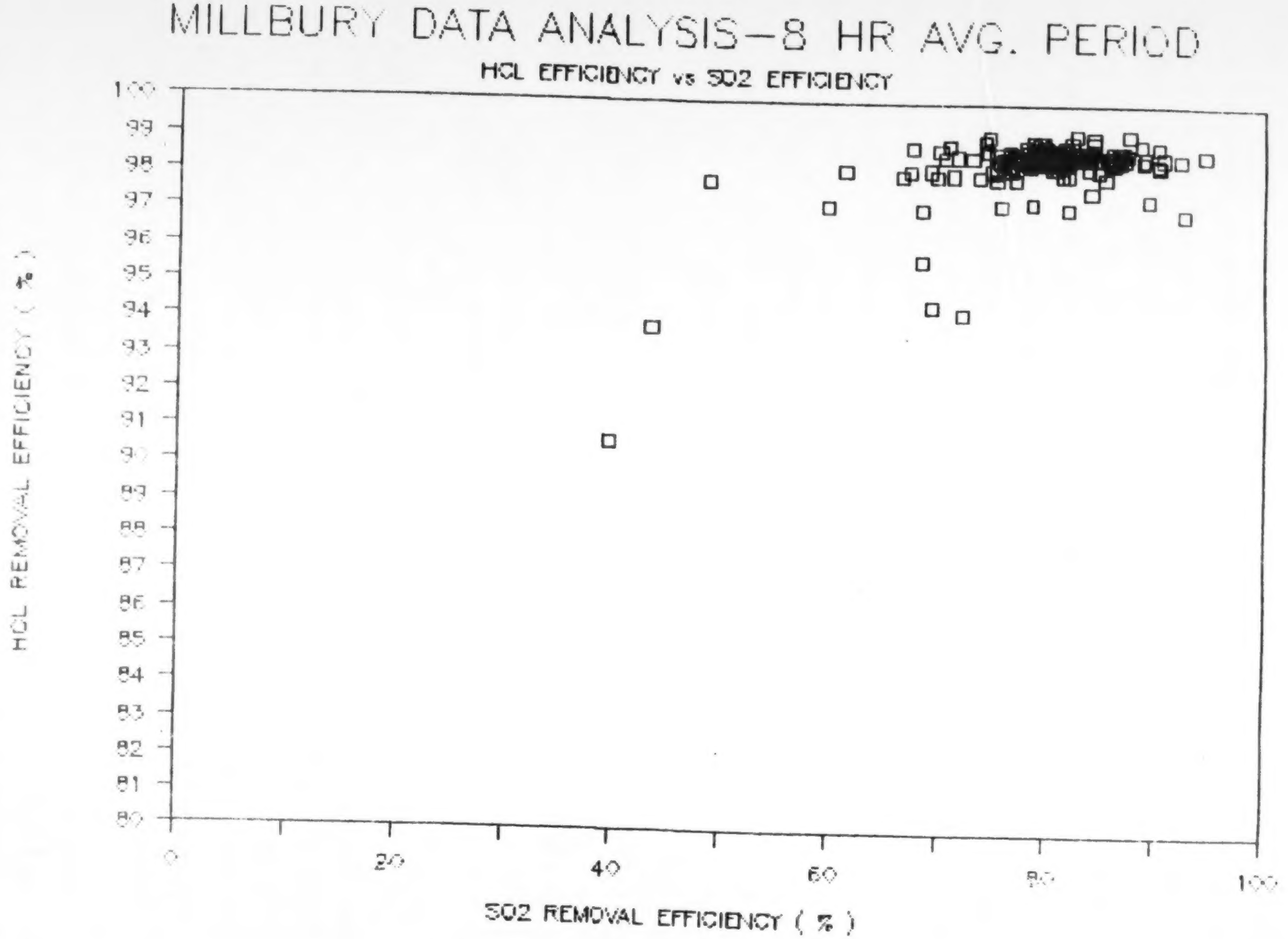

Figure A-4. HCl removal efficiency vs. $SO_2$ removal efficiency at Millbury (8-hour averages).

available dissolved calcium, operating conditions could exist during which there is insufficient dissolved calcium available to react with both HCl and $SO_2$. The fact that HCl removal efficiencies were high over the full range of operating conditions indicates there was a sufficient amount of dissolved calcium available relative to the total concentration of acid gas. In addition, Figures A-3 and A-4 indicate that the factors which influence $SO_2$ absorption (e.g., outlet gas temperatures and gas-liquid contact area) also control HCl absorption. As a result, HCl and $SO_2$ removal efficiencies tend to move in the same direction in response to changes in these factors.

Marion County Results. Unlike Millbury where data were collected over an extended period, emission data at the Marion County facility were collected during a series of 11 relatively short test runs of two to three hours each. For all test runs, the inlet HCl concentration averaged 650 ppm while the inlet $SO_2$ concentration averaged 330 ppm. Figure A-5 shows HCl removal efficiency versus $SO_2$ removal efficiency using the averages for each test run. Like Millbury, the Marion County results show a positive correlation between HCl removal efficiency and $SO_2$ removal efficiency. The lowest HCl removal efficiency (87 percent) corresponds to the lowest $SO_2$ removal efficiency (32 percent). All other HCl and $SO_2$ removal efficiency values were above this level. Similarly, the highest HCl removal efficiencies (98 percent) correspond to the highest $SO_2$ removal efficiencies (91 percent).

Like Millbury, the results from Marion County confirm the expectation of higher HCl removal efficiency relative to $SO_2$ removal. Similarly, the observations noted for the Millbury results related to excess calcium and factors controlling both HCl and $SO_2$ removal efficiencies also apply to the Marion County results.

Conclusions. The results from Millbury and Marion County indicate that HCl removal efficiency and $SO_2$ removal efficiency are positively correlated. Flue gas and spray dryer operating parameters that control $SO_2$ removal efficiency in a lime spray dryer also control HCl removal efficiency. In addition, HCl is absorbed preferentially to $SO_2$. These results indicate that, once the relationship between HCl removal efficiency and $SO_2$ removal efficiency has been established at a given facility, it should be possible to

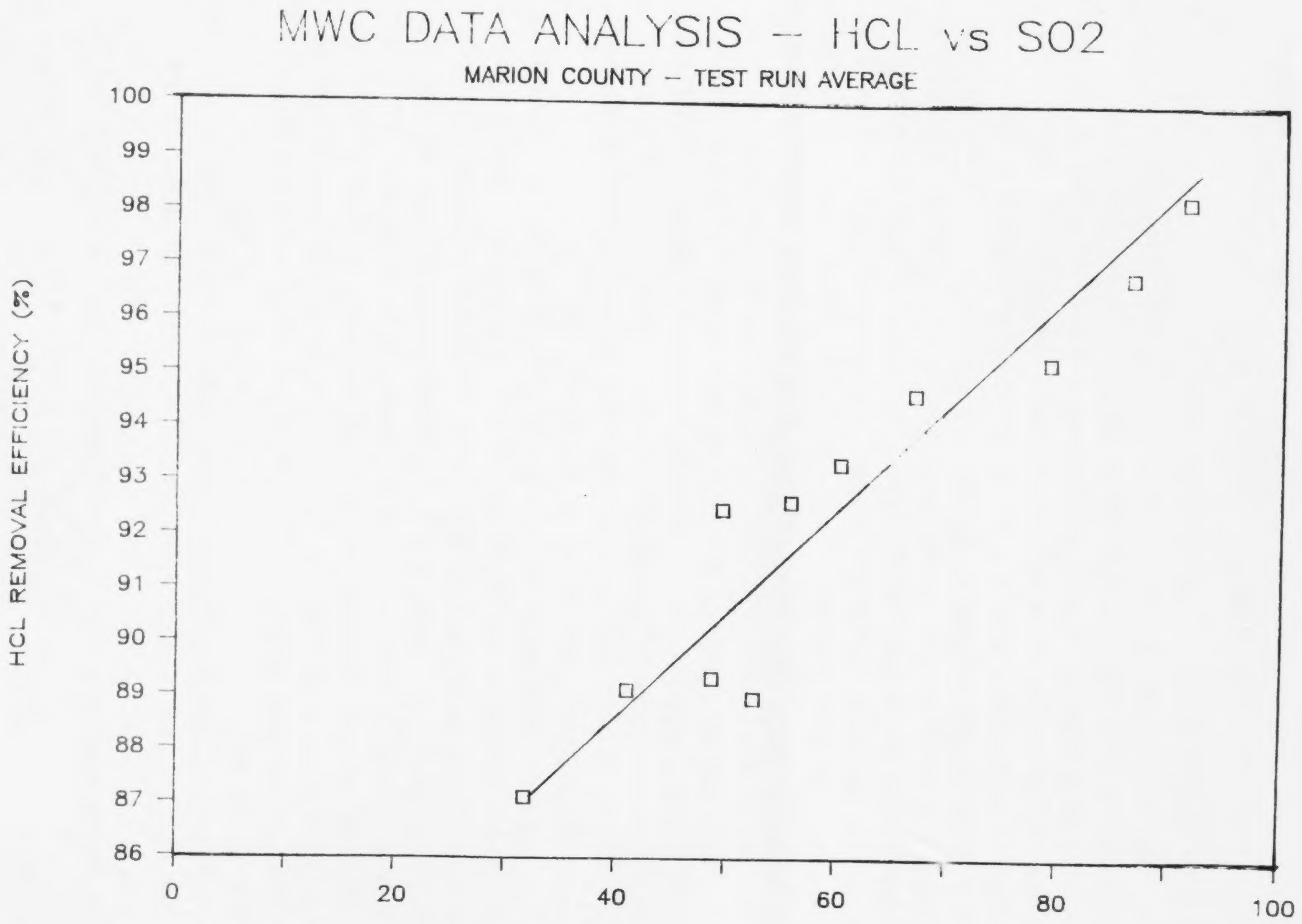

Figure A-5. HCl removal efficiency vs. $SO_2$ removal efficiency at Marion County (test run averages).

maintain HCl removal efficiency above a prescribed level by maintaining the $SO_2$ removal efficiency above a corresponding level.

### A.4.2 HCl Removal Efficiency Versus $SO_2$ Emissions

The objective of this analysis was to determine if an inverse relationship occurs between HCl removal efficiency and $SO_2$ emissions.

Millbury Results. A plot of HCl removal efficiency versus $SO_2$ emissions using 24-hour averages from Millbury is shown in Figure A-6. The data are generally scattered without a distinct relationship between HCl removal efficiency and $SO_2$ emissions. The HCl removal efficiencies generally fall between 97 and 99 percent, while the outlet $SO_2$ concentrations generally range from 20 to 60 ppm. During two of the 24-hour periods, higher $SO_2$ emissions were observed (72 and 97 ppm), yet HCl removal efficiencies were also high (98 to 99 percent). These two 24-hour periods represent periods in which inlet $SO_2$ concentrations were unusually high (both values were more than two standard deviations above the mean). The $SO_2$ removal efficiency for these periods, however, were near the mean value. These data suggest that the lack of a distinct relationship between HCl removal efficiency and $SO_2$ emissions may be associated with variations in inlet concentrations of both HCl and $SO_2$ as well as the limited range over which HCl removal levels were observed (i.e., between 95 and 99 percent).

A plot of HCl removal efficiency versus $SO_2$ emissions was also examined for 8-hour average values (see Figure A-7). This plot also failed to show a distinct relationship between HCl removal efficiency and $SO_2$ emissions for the same reasons discussed above. $SO_2$ emissions are more variable due to the shorter averaging times. The lowest 8-hour average HCl removal efficiencies (90 to 95 percent) are associated with $SO_2$ emissions of 40 to 60 ppm. The majority of the data, however, indicate that high HCl removal efficiencies (>98 percent) were achieved over a wide range of $SO_2$ outlet concentrations (10 to 100 ppm).

Marion County Results. The relationship between HCl removal efficiency and $SO_2$ emissions is more pronounced for the Marion County data (as shown in Figure A-8) than for the Millbury data, despite the fact that Marion County averaging times were shorter (2 to 3 hours). This is most likely due to the

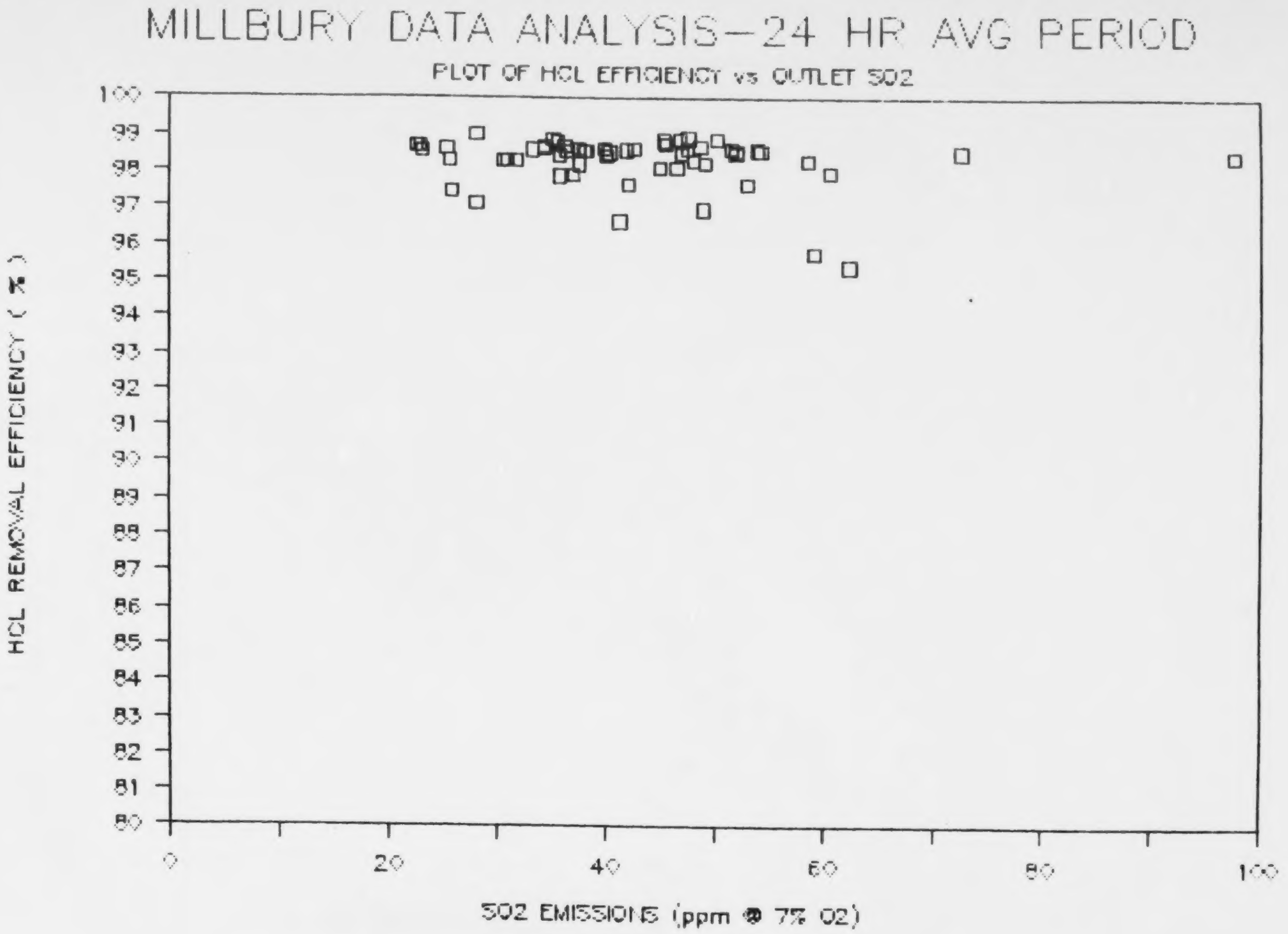

Figure A-6. HCl removal efficiency vs. $SO_2$ emissions at Millbury (24-hour averages).

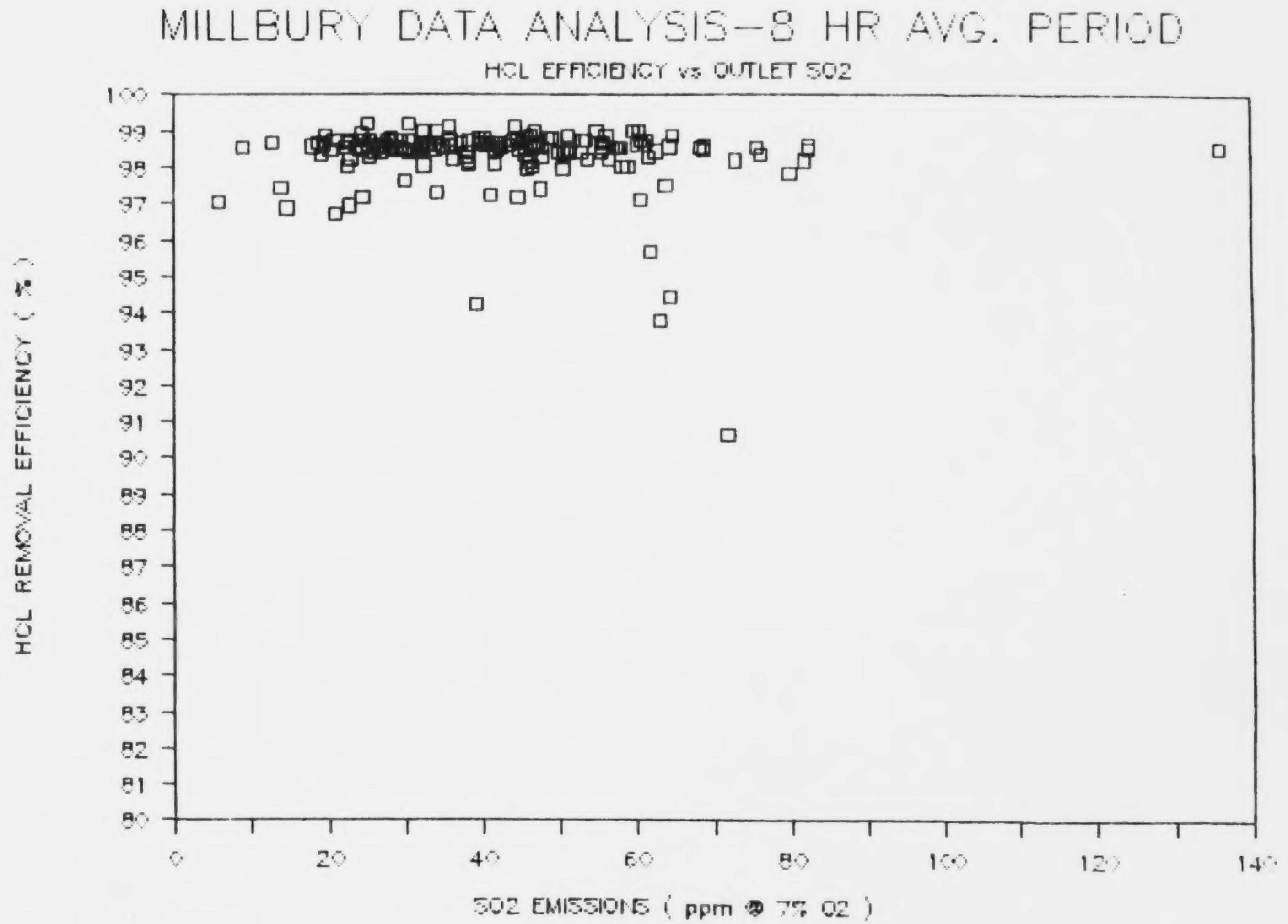

Figure A-7. HCl removal efficiency vs. $SO_2$ emissions at Millbury (8-hour averages).

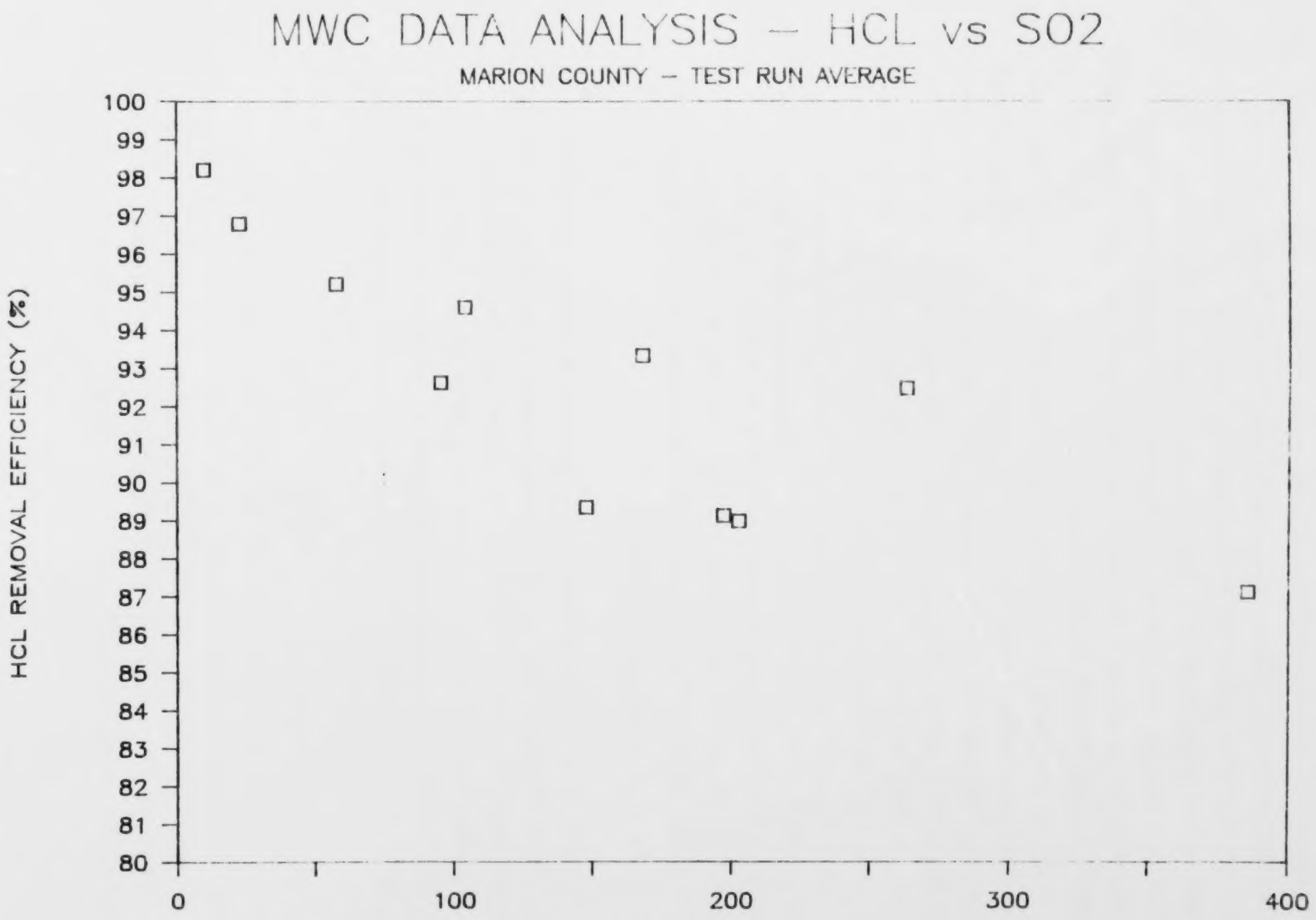

Figure A-8. HCl removal efficiency vs. $SO_2$ emissions at Marion County (test run averages).

wider range of HCl removal efficiencies observed during the Marion County characterization tests. These data clearly confirm the inverse relationship expected between HCl removal efficiency and $SO_2$ emissions--higher HCl removal efficiencies are associated with lower $SO_2$ emissions and vice-versa. The data show HCl removal efficiencies of greater than 95 percent when $SO_2$ emissions were below 60 ppm. At higher $SO_2$ concentrations (150 to 400 ppm), HCl removal ranged from 87 to 93 percent.

Conclusions. Analysis of emissions data from Millbury and Marion County indicate that HCl removal efficiency and $SO_2$ emissions are inversely related, although this relationship may be somewhat obscured by variations in inlet HCl and $SO_2$ levels and by the narrow range of HCl removal levels, as at Millbury. At both facilities, HCl removal efficiency remained above 95 percent when $SO_2$ emissions were maintained near or below 60 ppm. As an extension of the conclusion drawn above with respect to $SO_2$ removal efficiency, this analysis indicates that it should be possible to maintain HCl removal efficiency above a prescribed level by limiting $SO_2$ emissions. An analysis of variations in uncontrolled HCl and $SO_2$ may be necessary, however, before such a relationship can be established for a given facility.

## A.5 SULFUR DIOXIDE EMISSION VARIABILITY

This section discusses a statistical analysis performed to evaluate variability in $SO_2$ emissions and $SO_2$ percent reduction based on the CEM data from the Millbury facility. The impact of averaging time on emissions variability was also evaluated. Emission data from Marion County were not analyzed for variability because the data were collected over short time periods which are not suitable for time series analysis, an integral part of the variability assessment.

### A.5.1 Statistical Background[4,5]

Sulfur dioxide emissions from any MWC will vary with time. Municipal waste combustors equipped with a spray dryer system will exhibit a certain amount of variability in $SO_2$ emissions due to random fluctuations in the sulfur content of MSW and in spray dryer operating parameters such as outlet gas temperature, reagent quality, and liquid and gas flow rates.

There are several measures which describe the variability characteristics of $SO_2$ data:

- standard deviation and relative standard deviation,
- autocorrelation,
- probability distribution (normal vs. lognormal),
- length of averaging period and averaging method.

Standard deviation is an indicator of the spread of values; it measures the variation of measurements from the average. Relative standard deviation (RSD) is defined as the ratio of the standard deviation to the average or mean. The greater the standard deviation or RSD, the greater the variability in observed $SO_2$ emissions or percent reduction. Sulfur dioxide emission datasets which have the same mean $SO_2$ level but different $SO_2$ variability levels (standard deviations or RSDs) will have different maximum expected emissions.

Sequential measurements taken over a period of time are not necessarily independent observations. When emissions data are collected in sequence, there is a tendency for observations taken close together in time to be more alike than those taken farther apart. This association between observations in a time series is termed "autocorrelation". Autocorrelation can vary from -1.0 for inversely related observations to +1.0 for data which exhibit an extreme degree of positive association. Overall, the higher the autocorrelation factor, the higher the maximum expected emission level. The effect of autocorrelation on maximum expected emission values is especially important for longer averaging periods. However, autocorrelation is not as major a factor as RSD in determining emissions variability.

A first order autoregressive time series model, abbreviated as AR(1), is often used to project maximum expected $SO_2$ levels. The model assumes that an $SO_2$ emissions value at time t ($Y_t$) is related to the $SO_2$ emissions value measured for the previous period ($Y_{t-1}$) according to the equation:

$$Y_t = p_1 Y_{t-1} + e_t$$

where $e_t$ is random variation with an expected mean value of 0 and a variance assumed equal to the sample variance. The first order autocorrelation coefficient ($p_1$) is the estimate of the covariances of the emissions values based on a lag of one time period. This is the most basic autoregressive model and has been found in many cases to fit $SO_2$ emission and reduction time series measurements adequately. A discussion of the time series technique applied to data variability analysis is contained in References 4 and 5.

Observed $SO_2$ emissions data can be described by various probability distributions. Emissions data have generally been found to be well represented by either the normal or lognormal distribution. The primary difference in the two distributions is that the lognormal distribution (in which the natural logarithms of the data are normally distributed) is positively skewed; that is, there is an unusually large number of observations less than the mean.

The length of the averaging period also affects the variability of $SO_2$ emissions. The averaging period is defined as the period of time (hours or days) over which emission measurements are averaged. Longer averaging periods dampen the effects of variability and autocorrelation, resulting in lower maximum expected emission projections. A block average or a rolling average may be used to calculate average emission values. Block averages are computed on a separate, non-overlapping basis. Rolling averages are calculated by adding the most recent value to the data set and dropping the oldest value.

The final factor affecting maximum expected $SO_2$ emission values is the exceedance frequency. The exceedance frequency is expressed as the number of times, or percentage of time, that a given $SO_2$ emission value will be exceeded over a specified time period. The probability of exceeding a given emission value can be calculated for a specific averaging method and exceedance frequency. As an example, consider an 8-hour block averaging period and a one in one year exceedance frequency. There is a potential of having three exceedances each day using 8-hour block averages, or a total of 1095 potential exceedances over each year. Thus, one exceedance among the total potential exceedances results in an exceedance probability of 1/1095 or 0.00091. This exceedance probability, in turn, translates to a standard normal variate (or Z value) of 3.33. To estimate the maximum expected $SO_2$ emissions value (in this case, an 8-hour average value) under these conditions, an emission level is selected for which, in light of the sample distribution, standard deviation, and autocorrelation structure, there will be a 0.00091 probability in any of the 8-hour block average periods that $SO_2$ emissions will exceed the selected value. Over an extended period of time, the number of exceedances of the selected value will average one per year.

The same methodology described above for $SO_2$ emissions variability applies to $SO_2$ removal efficiency variability. The only difference is that investigators are usually concerned with minimum expected percent $SO_2$ removal efficiency rather than maximum expected $SO_2$ emission levels.

### A.5.2 Sulfur Dioxide Emissions Variability

The emission data collected at Millbury consist of hourly measurements taken over 62 consecutive days. As discussed above, time series analysis is an integral part of the variability assessment. To evaluate the structure of a time series, a set of 50 or more consecutive observations with few or no interruptions in the data is required. Three sets of $SO_2$ emissions data were available from the Millbury testing program which satisfied these criteria:

- 15 July to 31 July 1988 (Julian days 197 to 213),
- 4 August to 18 August 1988 (Julian days 217-231) and,
- 1 September to 14 September 1988 (Julian days 245-258).

The first step taken in evaluating the structure of the $SO_2$ emissions data was to develop a relative frequency plot of the data, as shown in Figure A-9. The fact that the sample probability distribution is skewed to the right suggests that the data fit a lognormal distribution, as opposed to a normal distribution. Plotting the logarithm of the emissions data on probability paper, as shown in Figure A-10, confirms that the lognormal distribution provides a close approximation of the sample distribution (perfect agreement would result in all the data falling on a straight line).

After selecting the sample probability distribution, the next step was to calculate the mean, standard deviation, and RSD for each of the three $SO_2$ emission data sets described above. These statistics are summarized in Table A-2 using the natural logarithm of the emissions data. The overall mean of the logarithms of the $SO_2$ emissions, 3.46, corresponds to a mean $SO_2$ emissions value of 32 ppm.

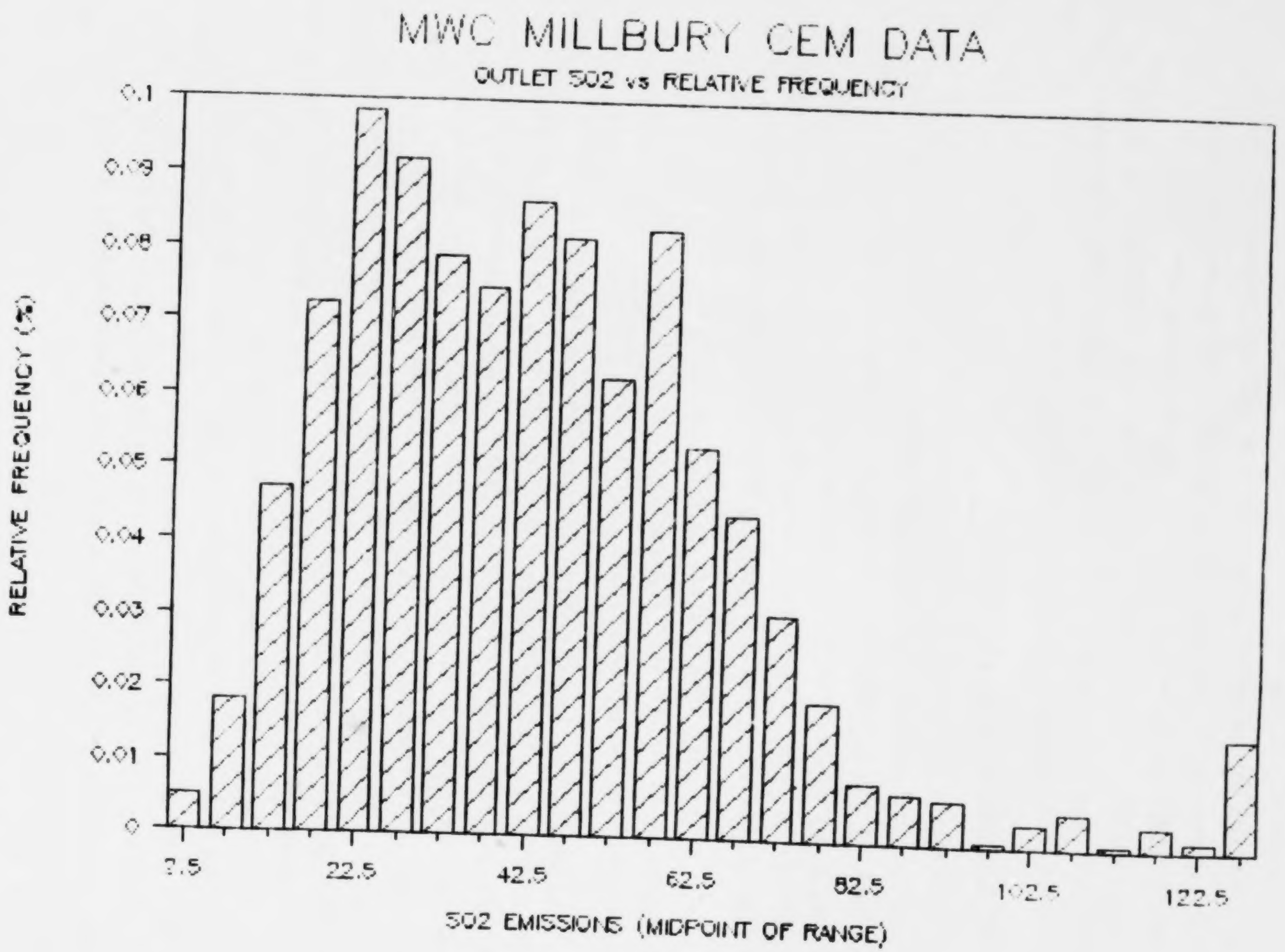

Figure A-9. Relative frequency distribution of $SO_2$ emissions at Millbury (hourly averages).

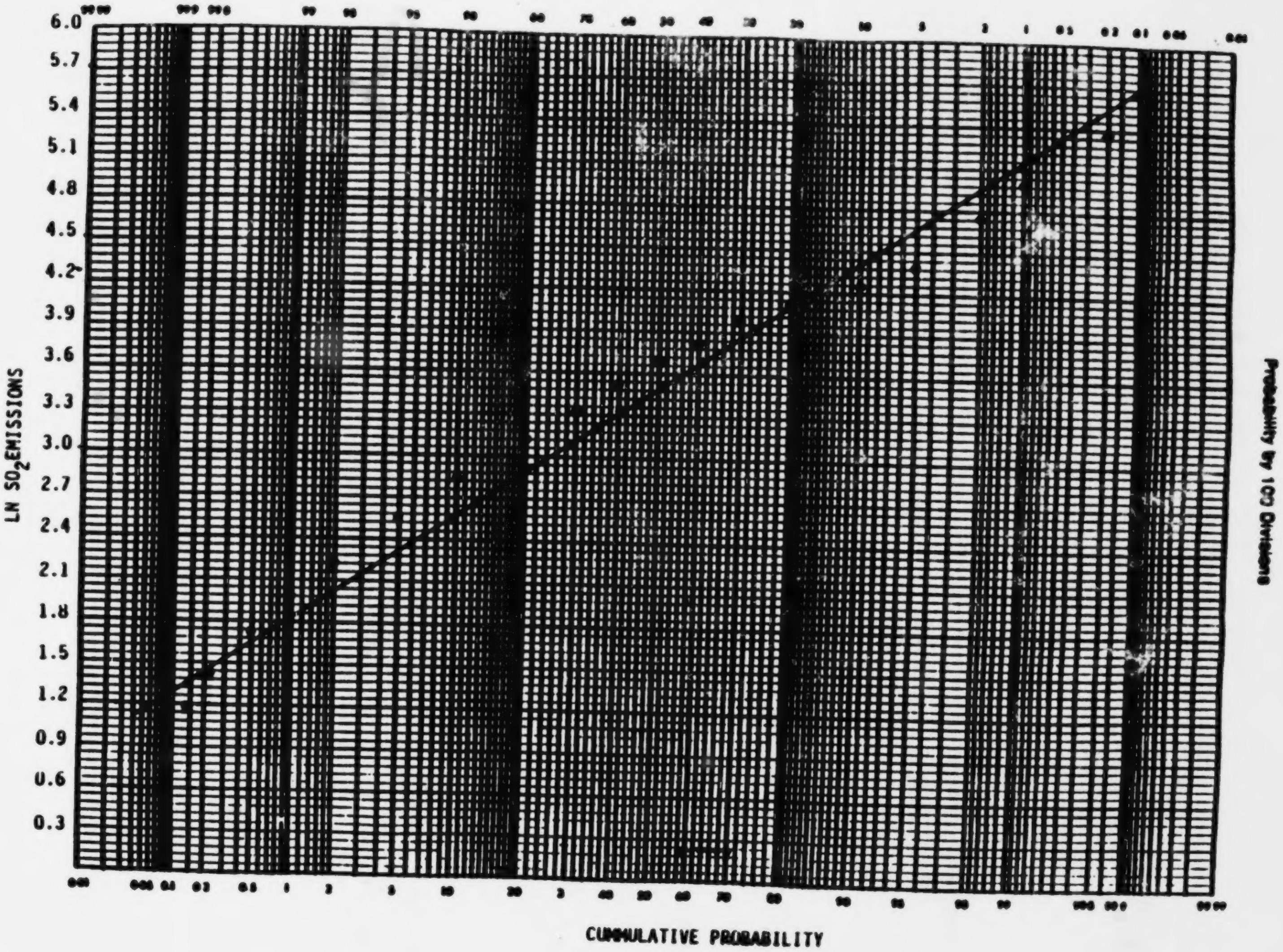

Figure A-10. Cumulative probability distribution of $SO_2$ emissions at Millbury (logarithms of hourly averages).

TABLE A-2. MILLBURY TEST VARIABILITY STATISTICS

| $SO_2$ Emissions Data | | Ln (Hourly $SO_2$ Emissions)[a] | | | |
|---|---|---|---|---|---|
| | | | | | First Order |
| Data Set | Period (Julian Days) | Mean | Standard Deviation | Relative Standard Deviation | Auto-correlation Coefficient |
| 1 | 197 - 213 | 3.34 | 0.59 | 0.18 | 0.66 |
| 2 | 217 - 231 | 3.46 | 0.65 | 0.19 | 0.65 |
| 3 | 245 - 258 | 3.61 | 0.49 | 0.14 | 0.69 |
| Overall | 197 - 258 | 3.46 | 0.59 | 0.17 | -- |
| $SO_2$ Removal Efficiency Data | | Ln (Hourly $SO_2$ Emissivity)[b] | | | |
| | | Mean | Standard Deviation | Relative Standard Deviation | Auto-correlation Coefficient |
| 4 | 251 - 258 | 3.11 | 0.25 | 0.08 | 0.63 |

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[a] Natural logarithm of hourly $SO_2$ emissions data

[b] Natural logarithm of hourly $SO_2$ emissivity data; $SO_2$ emissivity (%) = 100 - $SO_2$ removal efficiency (%)

To estimate the autocorrelation, the log-transformed $SO_2$ emission values were fit to a first-order autoregressive time series model, or AR(1). Each value of the time series is modeled as a regression function of the previous hour's value plus a random component. An AR(2) model, which uses the emission values for the two previous hours was also evaluated. However, a test of the significance of the second lag value in the AR(2) model showed that this coefficient is not significantly different from zero at the 95 percent confidence level. Therefore, the use of the AR(1) model is appropriate for these data.

The AR(1) model generated hourly autocorrelation coefficients between 0.65 and 0.69 for the three subject data sets, as shown in Table A-2. An overall autocorrelation coefficient cannot be calculated due to time gaps between the data sets. However, the autocorrelation results from the three data sets are in very close agreement. Thus, a "best estimate" of the $SO_2$ emissions hourly autocorrelation coefficient for the entire testing period is 0.67.

The results of the variability analysis are used to estimate the impact of averaging times and exceedance frequences on maximum expected $SO_2$ emission values using the methodology described in Reference 4. In estimating maximum expected values, the mean and standard deviation for the overall data set were used in conjunction with the "best estimate" autocorrelation coefficient of 0.67. The results are summarized in Table A-3. As an example, using a 24-hour block averaging period, the analysis projects that $SO_2$ emissions from the Millbury facility will exceed 76 ppm an average of one time in ten years. This compares with mean $SO_2$ emissions of 32 ppm. The analysis assumes, of course, that the facility continues to operate in the same manner as that observed during the emissions test period.

Inspection of Table A-3 shows that the difference between the maximum expected $SO_2$ emission value and the mean $SO_2$ emission level increases as the averaging period decreases and as the exceedance frequency decreases. The first result is due to the higher variability associated with short averaging times. The second result is due to the shape of the sample probability distribution, with most emission values clustered near the mean and fewer emission values distant from the mean.

## TABLE A-3. MAXIMUM EXPECTED $SO_2$ EMISSIONS AND MINIMUM EXPECTED $SO_2$ REMOVAL EFFICIENCIES BASED ON MILLBURY TEST DATA

Mean $SO_2$ emissions = 32 ppm
Mean $SO_2$ removal efficiency = 78 percent

| Exceedance Frequency/ Averaging Period | Maximum Expected $SO_2$ Emissions (ppm $SO_2$) | Minimum Expected $SO_2$ Removal (percent) |
|---|---|---|
| One in 10 Years Exceedance Frequency | | |
| 1-Hour Block Average | 391 | 35 |
| 3-Hour Block Average | 233 | 49 |
| 8-Hour Block Average | 137 | 60 |
| 24-hour Block Average | 76 | 69 |
| 7-Day Rolling Average | 45 | 74 |
| 30-Day Rolling Average | 38 | 76 |
| One in 1 year Exceedance Frequency | | |
| 1-Hour Block Average | 268 | 45 |
| 3-Hour Block Average | 173 | 55 |
| 8-Hour Block Average | 109 | 64 |
| 24-hour Block Average | 65 | 71 |
| 7-Day Rolling Average | 42 | 75 |
| 30-Day Rolling Average | 36 | 76 |
| One Percent Exceedance Frequency | | |
| 1-Hour Block Average | 126 | 60 |
| 3-Hour Block Average | 103 | 64 |
| 8-Hour Block Average | 80 | 68 |
| 24-Hour Block Average | 58 | 72 |
| 7-Day Rolling Average | 40 | 75 |
| 30-Day Rolling Average | 36 | 77 |

### A.5.3 Sulfur Dioxide Removal Efficiency Variability

To calculate $SO_2$ removal efficiency, both spray dryer inlet and outlet $SO_2$ (as well as $O_2$) measurements are required. Due to gaps in available CEM data for inlet and outlet $SO_2$ measurements during early phases of the Millbury emission test, and the requirement for 50 or more hourly measurements with few or no interruptions, analysis of removal efficiency variability with the Millbury data was restricted to the last eight days (a total of 192 observations) of the test period. During this final period, four instances of missing $SO_2$ removal efficiency data were encountered in which one or two hourly values were unavailable due to CEM sampling system malfunctions. These missing values were replaced with the mean; this is a standard procedure in time series analysis and does not materially affect autocorrelation coefficient estimation.

As with $SO_2$ emissions data, the first step in the $SO_2$ removal efficiency variability analysis was to select an appropriate probability distribution. With percent removal data, past experience has shown that the data are easier to manipulate and evaluate when expressed as $SO_2$ emissivity. $SO_2$ emissivity is a measure of the percentage of the inlet $SO_2$ concentration which is emitted by the control device and is given by the expression:

$$SO_2 \text{ emissivity } (\%) = 100 - SO_2 \text{ removal efficiency } (\%)$$

The relative frequency plot of the $SO_2$ emissivity data from the last eight days is shown in Figure A-11. As with the $SO_2$ emissions data, the skewed distribution suggests a lognormal sample probability distribution. Figure A-12 shows the plot of the natural logarithms of $SO_2$ emissivity data on probability paper. The straight line approximation in this figure supports the selection of the lognormal distribution as a close approximation of the sample distribution.

Sample statistics for the log-transformed $SO_2$ emissivity data are also shown in Table A-2. The logarithmic sample mean of 3.11 for $SO_2$ emissivity corresponds to 77.6 percent $SO_2$ removal efficiency.

As with $SO_2$ emissions data, an AR(1) model was used to estimate the autocorrelation coefficient of the log-transformed $SO_2$ emissivity data. The AR(2) model was also evaluated, but was rejected due to insignificance of the

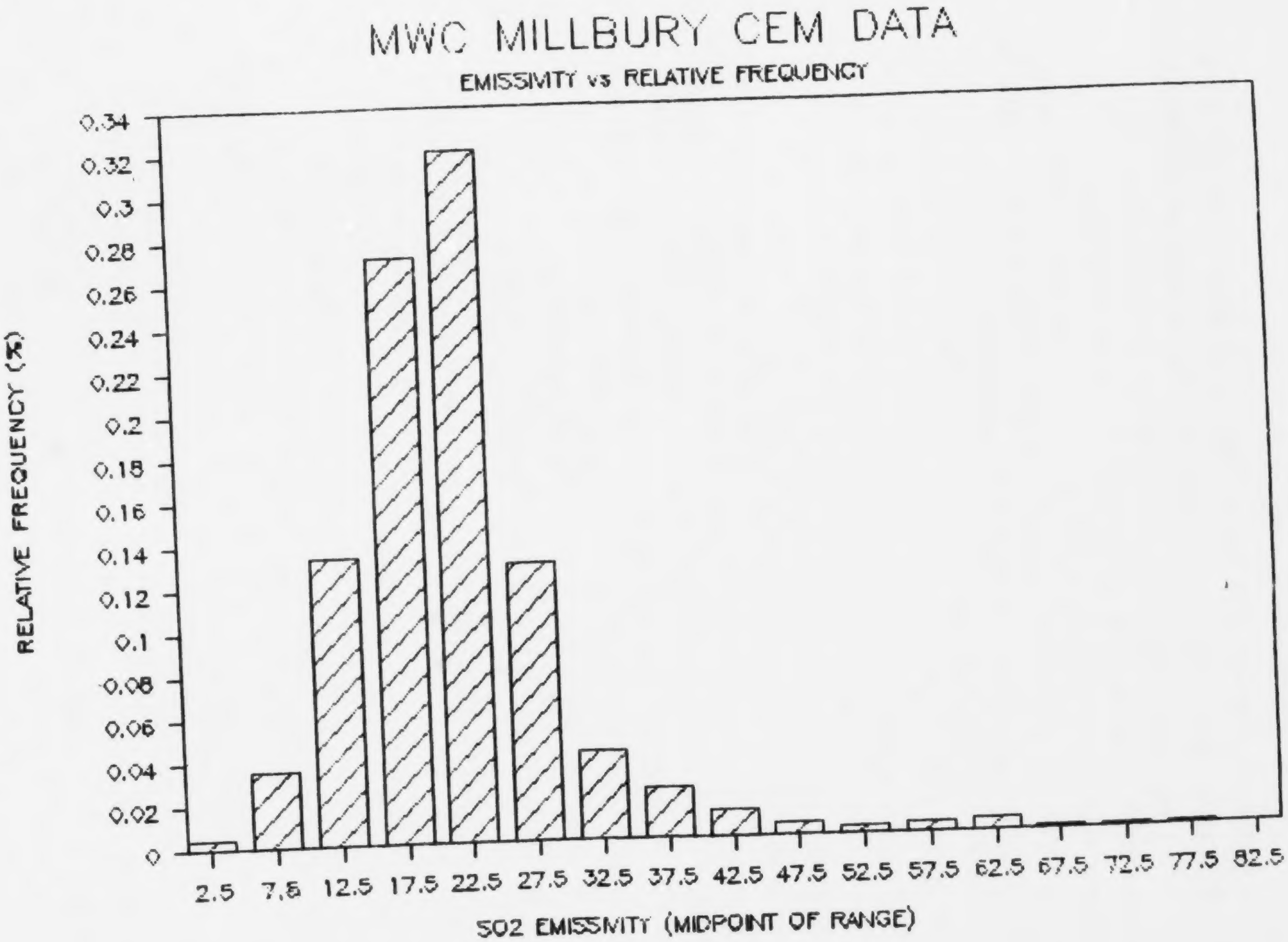

Figure A-11. Relative frequency distribution of $SO_2$ emissivity at Millbury (hourly averages).

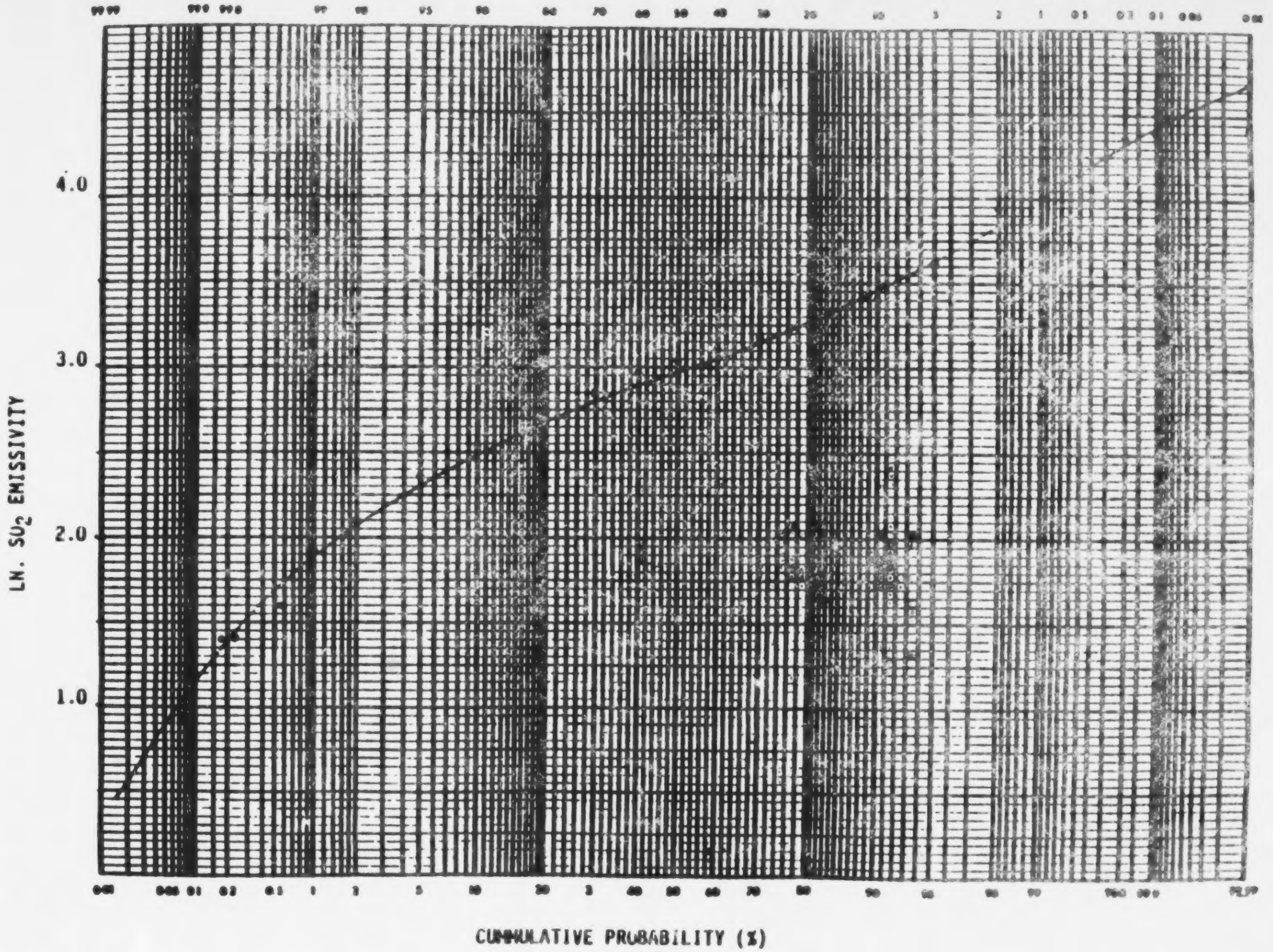

Figure A-12. Cumulative probability distribution of SO$_2$ emissivity at Millbury (logarithms of hourly averages).

second lag coefficient. The AR(1) model, considered the best model for these data, estimated an autocorrelation coefficient of 0.53 for the hourly emissivity data.

This autocorrelation coefficient, in conjunction with the mean and standard deviation statistics, was used to estimate the impact of averaging times and exceedance frequencies on minimum expected $SO_2$ removal efficiency in the same manner as described above for maximum $SO_2$ emission values (see Table A-3). Using the same example 24-hour block averaging period as before, the analysis projects that the $SO_2$ removal efficiency of the Millbury spray dryer/ESP will fall below 69 percent an average of only one time in ten years. This compares with mean $SO_2$ percent removal of 78 percent.

The table shows that the same general trends apply to minimum expected $SO_2$ removal levels (i.e., difference between projected minimum and the mean) resulting from changes in averaging times and exceedance frequencies as discussed above for $SO_2$ emissions. The factors underlying these trends are also the same.

## REFERENCES

1. Entropy Environmentalists, Inc. Emission Test Report, Municipal Waste Combustion Continuous Emission Monitoring Program, Wheelabrator Resource Recovery Facility, Millbury, Massachusetts. Prepared for U.S. Environmental Protection Agency, Research Traingle Park, NC. January 1989. Emission Test Report 88-MIN-07C.

2. Anderson, C. L., Vancil M. A., Mayhew, J. W., and Holder, D. J. (Radian Corporation). Characterization Emission Test Report, Marion County Solid Waste to Energy Facility. Prepared for U.S. Environmental Protection Agency. September 1988. EMB Report No. 87-MIN-04, Volume I. pp. 4-1 to 4-3.

3. U.S. Environmental Protection Agency. Municipal Waste Combustion Study: Flue Gas Cleaning Technology. June 1987. EPA/530-SW-87-021d. p. 4-4.

4. Radian Corporation. Determination of Mean $SO_2$ Emission Levels Required to Meet A 1.2 lb $SO_2$/Million Btu Emission Standard for Various Averaging Times and Compliance Policies. Prepared for the U.S. Environmental Protection Agency. EPA Contract No. 68-02-3816. Research Trinagle Park, North Carolina. March 1985.

5. U.S. Environmental Protection Agency. Statistical Analysis of Emission Test Data from Fluidized Bed Combustion Boilers at Prince Edward Island, Canada. Publication No. EPA-450/3-86-015. December 1986.